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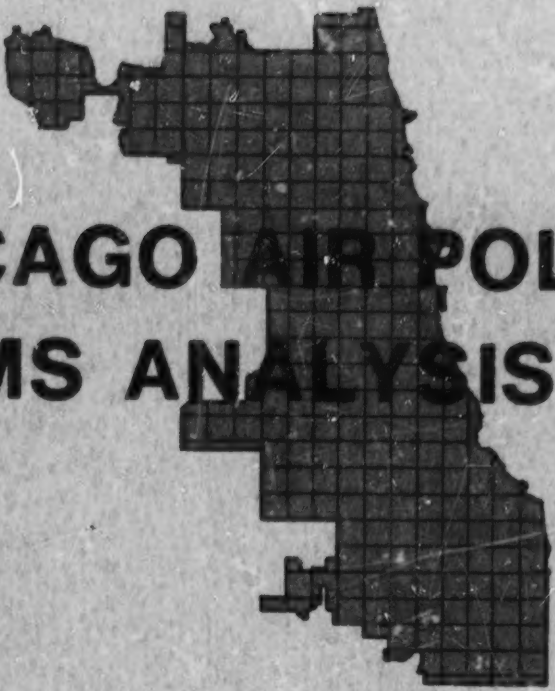

CHICAGO AIR POLLUTION SYSTEMS ANALYSIS PROGRAM

AN URBAN ATMOSPHERIC DISPERSION MODEL

J. J. Roberts, E. J. Croke, and A. S. Kennedy

ARGONNE NATIONAL LABORATORY

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CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL

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DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
NATIONAL AIR POLLUTION CONTROL ADMINISTRATION

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Meteorology

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CHICAGO AIR POLLUTION SYSTEMS ANALYSIS PROGRAM

ARGONNE NATIONAL LABORATORY
CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL
DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
National Air Pollution Control Administration

An Urban Atmospheric Dispersion Model

October 1969

by

J. J. Roberts
E. J. Croke
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FOREWORD

The City of Chicago Air Pollution Systems Analysis Study discussed in this report represents a joint effort conducted and funded by the Atomic Energy Commission, the Department of Health, Education and Welfare and the Chicago Department of Air Pollution Control.

Program direction, system analysis and computer programming are provided by the Argonne National Laboratory. Meteorology studies and computer model development are performed by Argonne and the National Center for Air Pollution Control, Cincinnati, Ohio. The Chicago Department of Air Pollution Control supplies emission and air quality data for the atmospheric dispersion studies.

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An Urban Atmospheric Dispersion Model*

J.J. Roberts, E.J. Croke, A.S. Kennedy

Summary

A multiple source, computerized atmospheric dispersion model designed for operational use in air resource management has been formulated and programmed for the IBM 360-75 system. This "integrated puff" model provides a more realistic physical simulation of the processes of smoke plume dispersion than has hitherto been employed, since it provides for simulation of near-zero wind speed conditions, models three-dimensional wind vector variation and atmospheric diffusion in three dimensions, including upwind-downwind diffusion, and permits variation of stability and mixing layer depth with time.

This paper describes the development and preliminary validation testing of the model against data from a three-year, computerized inventory of sulfur dioxide air quality data recorded by the receptors of the Chicago, Illinois, telemetered air monitoring system.

A detailed, two-year inventory of Chicago coal and oil burning SO_2 emission sources was acquired, data storage formats were designed, and computer algorithms were developed to generate hourly average estimates of emissions from major utility, industrial, residential, commercial, and institutional sources. Small emitters were aggregated into square mile area sources.

Meteorology data from local U.S. Weather Bureau stations and radiosonde balloon stations was acquired in computer tape format. Algorithms were developed to process this information in order to provide inputs of critical parameters, including mixing layer altitude and atmospheric stability.

The model itself consists of a series of algorithms assembled around a kernel which represents the transport and diffusion of pollutant species from point and area sources according to a Gaussian distribution in three dimensions. This

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* Work jointly sponsored by the National Air Pollution Control Administration, the Atomic Energy Commission, and the Chicago Department of Air Pollution Control. Presented at the Symposium on Multiple Source Urban Diffusion Models, University of North Carolina, Chapel Hill, N. C., October 27-30, 1969.

kernel, which represents a three-dimensional puff of smoke, is integrated according to a time-series of piecewise constant wind vectors and piecewise constant atmospheric stability parameters to simulate the transient behavior of a continuous smoke plume. Smoke plume rise and downwash phenomena are simulated.

The model is incorporated in a master air pollution data management system which is employed to store, retrieve, process, analyze, and display emission, meteorology, and air quality data. This system is used for micrometeorological dispersion studies, to form and input data arrays, and to validate the theoretical predictions of the model against recorded air quality data.

At present, the model is in the early stages of validation and has been tested against one month of hourly average SO_2 data from five Chicago air quality monitoring stations. Thus a statistical sample of approximately 2300 data points is presently available. The performance of the model, tested against this limited sample, appears to be quite good. The ratio of standard deviation to mean values for all hourly SO_2 predictions is 0.93. For six-hour average predictions, this ratio is 0.64 and for 24-hour average predictions it drops to 0.43. Over 66% of the 24-hour average SO_2 predictions are within ± 0.05 ppm of observed values and approximately 90% are within ± 0.1 ppm of actual dosages.

Hourly time series plots of observed and actual SO_2 concentrations indicate that the model is sufficiently accurate to test selective hypotheses about the model itself and to evaluate urban air resource management strategies.

1.0 Introduction

A multiple source, computerized atmospheric dispersion model has been formulated and programmed for the IBM 360-75 system. This "integrated puff" model provides a more realistic physical simulation of the processes of smoke plume dispersion than has hitherto been employed, since it provides for simulation of near-zero wind speed conditions, models three-dimensional wind vector variation and atmospheric diffusion in three dimensions, including upwind-downwind diffusion, and permits variation of stability and mixing layer depth with time.

A source-oriented model is essential for the development of optimal incident control strategies and long range abatement plans. For example, a preliminary version of the integrated puff model was programmed and employed to develop a prototype optimal control model for the urban power plant network (Croke and Kennedy, 1969). The model will be used in combination with Chicago's emission inventory data as the primary analytical tool in the performance of a series of air pollution system analysis studies. These include:

a) Cost-effectiveness studies of alternative control strategies for specific source aggregates such as power plants, the food processing industry, the steel industry, asphalt batching, etc.

b) Development of rapid-response, automated optimal incident control strategies for the urban power plant network, optimal gas allocation to dual fuel sources, process emission control, etc., using mathematical programming and other operations research techniques.

c) Development of long range air pollution abatement plans will be oriented around the computer simulation of the city combined with projections of its population, fuel use, production and transportation network growth patterns. Emission control legislation, zoning ordinances, etc., can be tested in a simulation of the Chicago urban area of the future, and cost-effectiveness studies can be performed to evaluate the economic impact of pollution abatement measures.

The model described in this paper has several important aspects in common with earlier efforts (e.g. Koogler, 1967; Turner, 1964; Clarke, 1964):

1) An emission inventory is developed; large emitters are considered as point sources and smaller residential commercial and industrial emitters homogenized as area sources in a standard grid.

2) A mathematical algorithm (typically based on the representation of turbulent diffusion by a Gaussian distribution) is used to describe the advection and diffusion of plumes from each of the sources or source areas.

3) Contributions from individual plumes are summed and sometimes integrated over time to give pollution doses at arbitrary locations.

4) The model is validated by statistical comparison with field measurements taken by an array of monitors.

5) While the results of the validation study may indicate a refinement of certain physical assumptions (such as the plume rise formulation) or inclusion of additional sources (such as distant power plants),

> no further improvement by linear regression or similar curve fitting techniques is permitted; that is, the model is not tuned to a particular receptor or city. This last point is particularly important if the model is to be used in the development of incident control strategies and long range urban planning.

In essence, an air pollution dispersion model is a collection of algorithms, a set of assumptions and subsequent calculations for every stage of the analysis, from the compilation of the emission inventory to the validation of the results. These are discussed briefly in the following sections.

2.0 Development of an Emission Inventory

A major task element of the Chicago Air Pollution Systems Analysis Program was the development of an inventory of hourly average emissions for the power plants and industrial, residential, commercial, and institutional SO_2 sources which are the primary contributors to Chicago's sulfur oxide air pollution problem.

Figure 2.1 shows the location and distribution of the largest individual coal and oil burning sources of sulfur oxides, while Figure 2.2 shows the source density of residential emitters which were too numerous to inventory individually. Figure 2.3 depicts the distribution and magnitude, by source category, of Chicago's SO_2 emitters.

2.1 The Chicago Air Quality Monitoring System

Chicago operates a network of eight telemetered air monitoring (TAM) stations, which continuously and automatically record five-minute average SO_2 concentrations at 15-minute intervals throughout the day. The data recorded by these stations during 1966 and 1967 is typical of a city which is characterized by a highly unhomogeneous SO_2 source distribution and density. Table 2.1 provides a summary of the air quality situation of Chicago as recorded by the network of TAM stations.

Since the source density, type, and distribution in the immediate vicinity of a receptor may, under certain meteorological conditions, dominate the ambient air quality recorded, it is of value to examine the record of the eight TAM stations from the standpoint of their proximity to Chicago's SO_2 sources. This exercise is particularly useful, since it provides an indication of what types of sources are

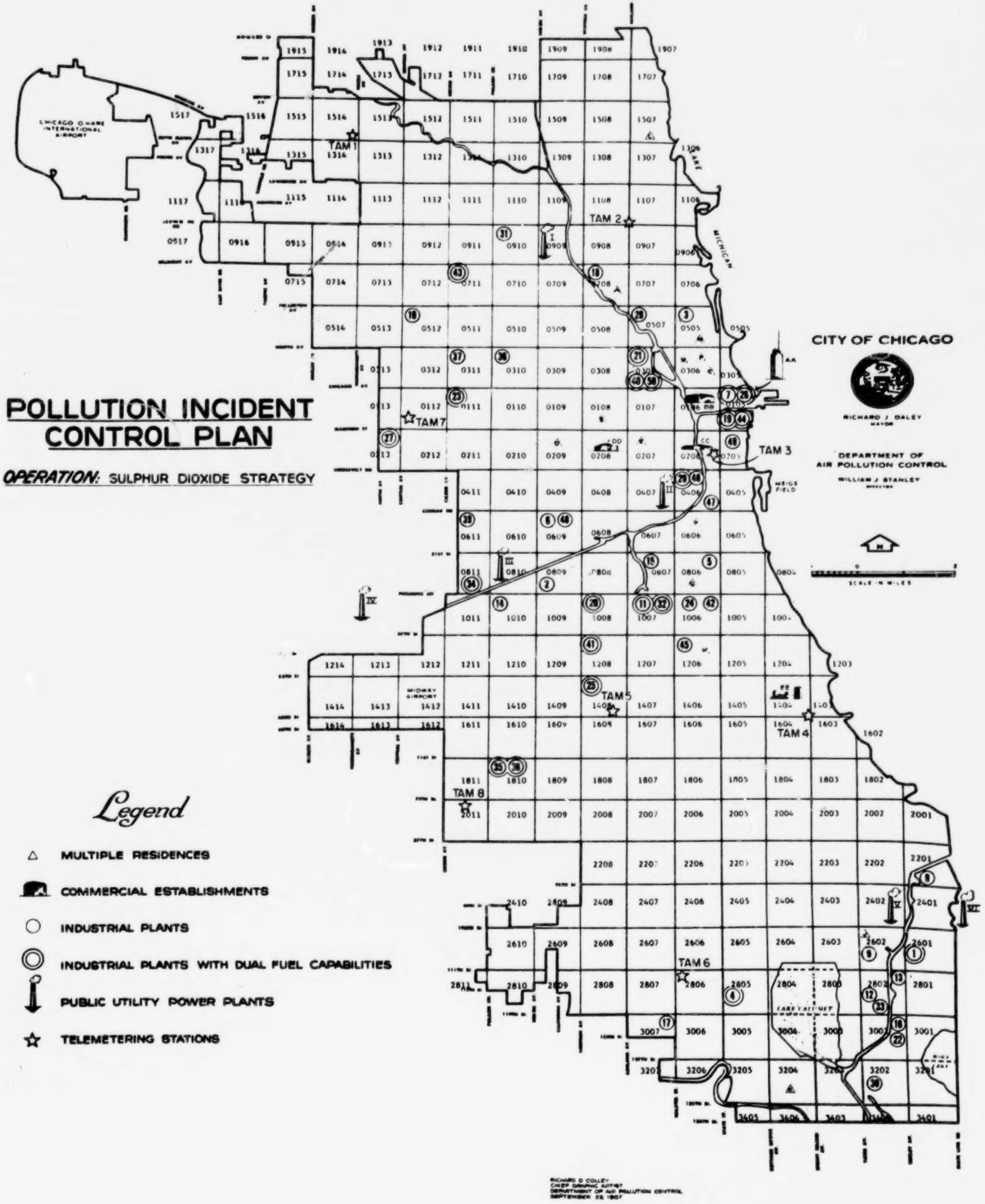
POLLUTION INCIDENT CONTROL PLAN
OPERATION: SULPHUR DIOXIDE STRATEGY
CITY OF CHICAGO
RICHARD J. DALEY MAYOR
DEPARTMENT OF AIR POLLUTION CONTROL
WILLIAM J. STANLEY DIRECTOR
SCALE IN MILES
CHICAGO O'HARE INTERNATIONAL AIRPORT
MIDWAY AIRPORT
MEIGS FIELD
LAKE MICHIGAN
LAKE CALUMET
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
TAM 6
TAM 7
TAM 8
Legend
△ MULTIPLE RESIDENCES
COMMERCIAL ESTABLISHMENTS
○ INDUSTRIAL PLANTS
◎ INDUSTRIAL PLANTS WITH DUAL FUEL CAPABILITIES
PUBLIC UTILITY POWER PLANTS
☆ TELEMETERING STATIONS
RICHARD O COLLEY
CHIEF GRAPHIC ARTIST
DEPARTMENT OF AIR POLLUTION CONTROL
SEPTEMBER 22, 1967

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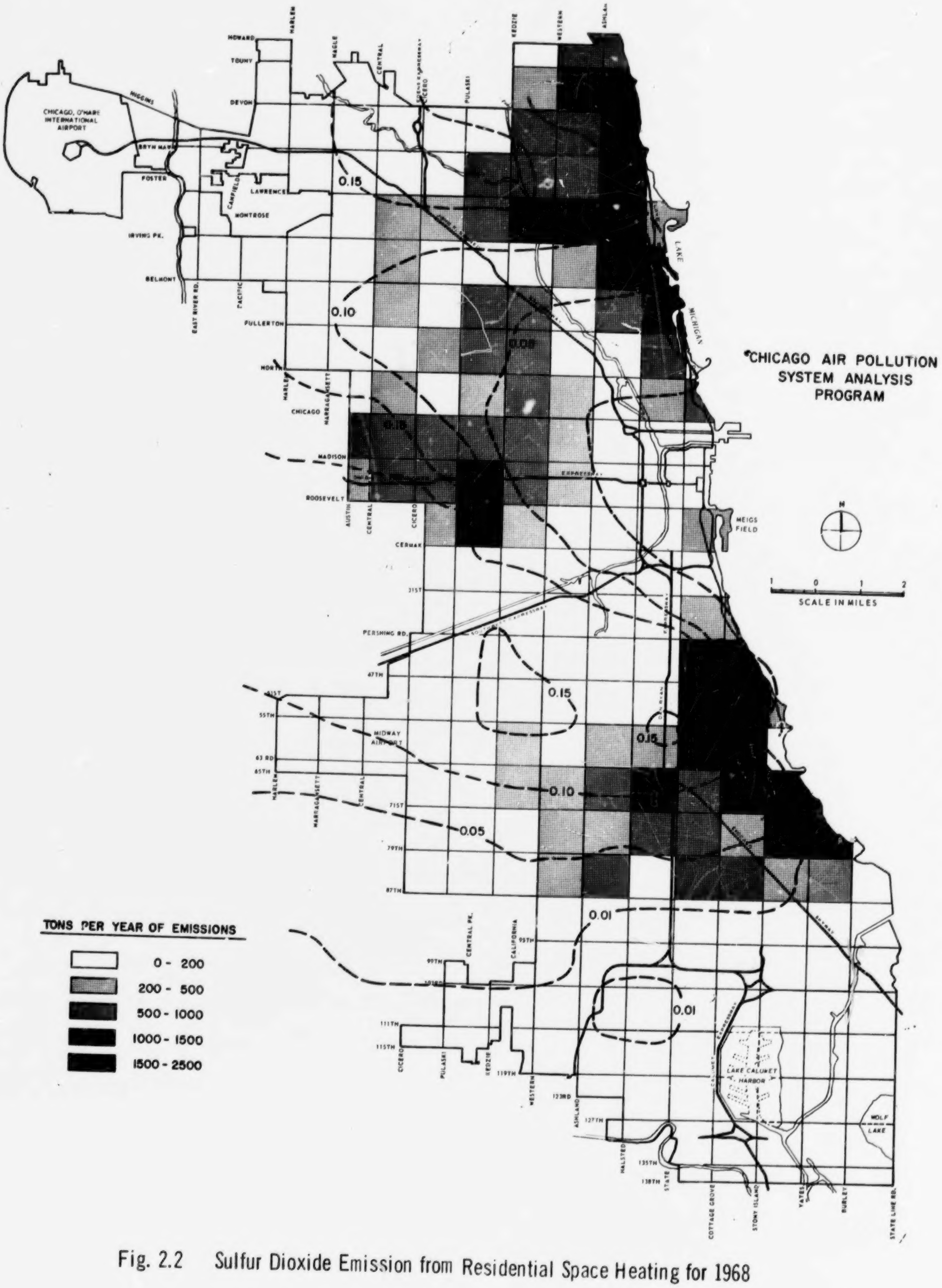
Fig. 2.1 Chicago Map of Major Sources


CHICAGO AIR POLLUTION
SYSTEM ANALYSIS
PROGRAM
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200 - 500
500 - 1000
1000 - 1500
1500 - 2500
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SCALE IN MILES
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CHICAGO, O'HARE INTERNATIONAL AIRPORT
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HOWARD
TOUHY
DEVON
BRYN MAWR
FOSTER
LAWRENCE
MONTROSE
IRVING PK.
BELMONT
FULLERTON
NORTH
CHICAGO
MADISON
ROOSEVELT
CERMAK
31ST
PERSHING RD.
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127TH
135TH
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HARLEM
NAGLE
CENTRAL
CICERO
PULASKI
KEDZIE
WESTERN
ASHLAND
EAST RIVER RD.
PACIFIC
CANFIELD
NARRAGANSETT
AUSTIN
MIDWAY AIRPORT
CENTRAL PK.
CALIFORNIA
HALSTED
STATE
COTTAGE GROVE
STONY ISLAND
YATES
BURLEY
STATE LINE RD.
LAKE MICHIGAN
MEIGS FIELD
LAKE CALUMET HARBOR
WOLF LAKE
EXPRESSWAY
0.15
0.10
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0.15
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0.01
0.01

Fig. 2.2 Sulfur Dioxide Emission from Residential Space Heating for 1968

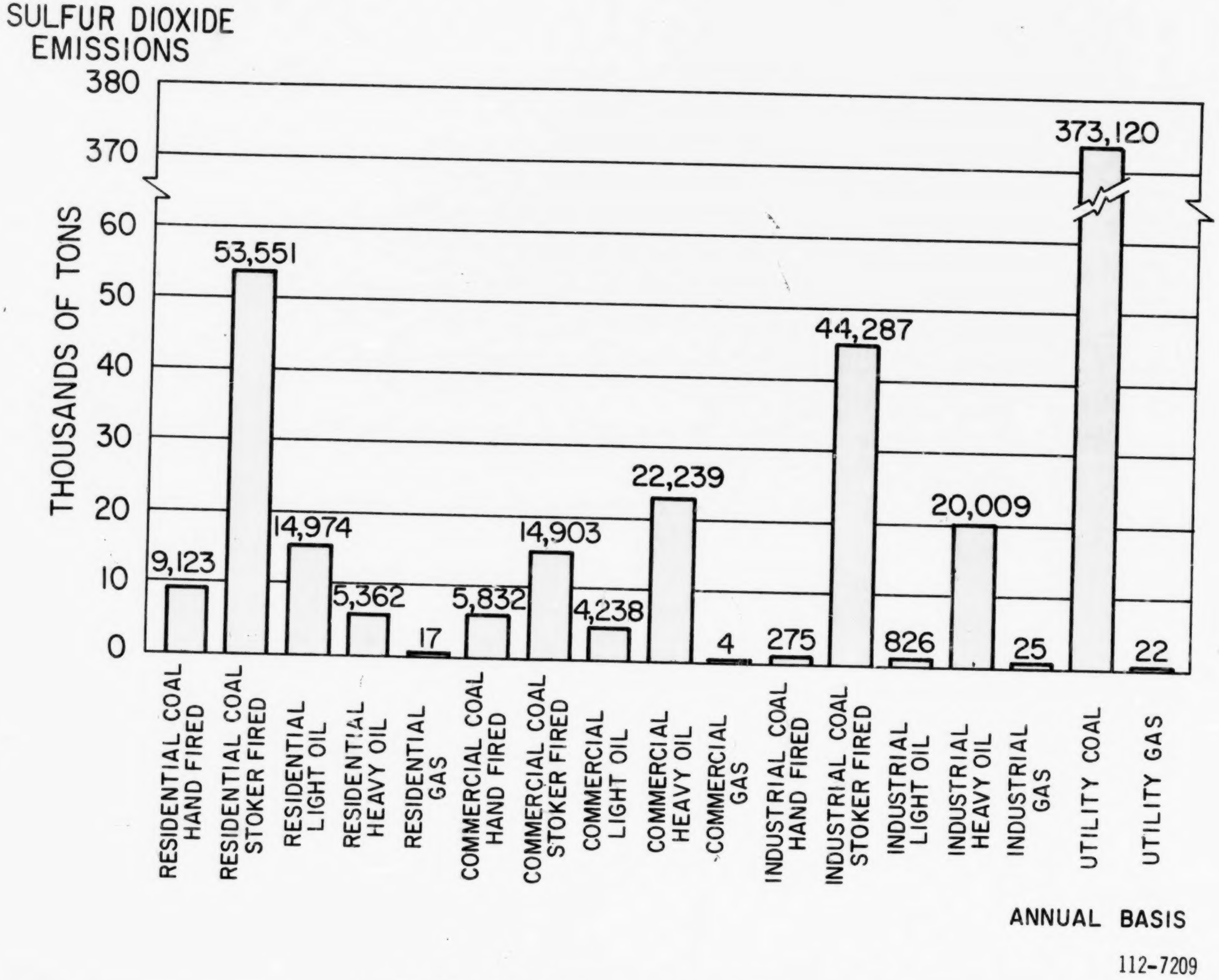

Fig. 2.3 Sulfur Dioxide Source Distribution

likely to have the predominant effect on the recorded air quality, and therefore serves as an indicator of the level of effort that should be expended to develop a detailed emission inventory. Moreover, an understanding of the distribution of sources relative to each of the monitoring stations which provide the data required to validate the Chicago atmospheric diffusion model illuminates and explains certain of the results predicted by the model. Table 2.1 shows the distribution of one-hour SO_2 dosages recorded at the eight TAM stations.

TABLE 2.1

Total Number of Recorded One-hour SO_2 Dosages (1966-67)

TAM Station	G.T. 0.2 PPM	G.T. 0.3 PPM	G.T. 0.4 PPM	G.T. 0.5 PPM
1	182	59	18	5
2	618	203	70	30
3	3210	1838	975	483
4	1990	966	491	268
5	525	207	84	45
6	364	169	94	65
7	934	332	122	35
8	206	51	15	6

TAM Station 1

TAM station 1 is located near the northwestern limits of Chicago in an area which is characterized by residential neighborhoods of relatively recent construction and a limited amount of light industrial development. Heating plants in this sector of the city are predominantly natural gas fired and relatively little coal or oil is consumed by industrial or commercial sources. TAM 1 is thus sited in a relatively clean section of the city, insofar as sulfur oxide emissions are concerned. This conclusion is borne out by the fact that TAM 1 has recorded high ambient SO_2 concentrations at least one order of magnitude less frequently than do monitoring stations located nearer to the urban core area. (See Table 2.1)

TAM Station 2

Station 2, located in the northeast sector of the city approximately 1.5 miles from the lakeshore, is in a mixed industrial-residential area which contains a large concentration of high-rise coal, oil and gas fired residential structures. The prevailing southwesterly flow tends to transport SO_2 from the central utility-industrial cluster into this area, but average dosages tend to be relatively low because of the comparatively large transport distances involved. This is evidenced by the relatively high ratio of low to high concentrations recorded at TAM 2 (Table 2.1) compared to the record for TAM 3 or TAM 4 where localized coal and oil burning sources are more significant. The nearest major SO_2 source to TAM 2 is a moderate sized coal fired power plant which is located approximately 1.5 miles to the southwest.

TAM Station 3

This receptor is centrally located atop a large office building in the Chicago loop business district. As such, it is not only surrounded by a cluster of large commercial and institutional space heating sources, but is situated directly northeast of a major concentration of industrial plants and a line formed by the three largest power plants within the city limits. Since the prevailing flow is southwesterly, a high incident frequency due to this industrial-utility concentration and to local space heating effects is to be expected at TAM 3. As indicated in Table 2.1, this station is, in fact, located in the most polluted sector of the city.

TAM Station 4

TAM 4 is located in the south-central Hyde Park area of Chicago within one mile of Lake Michigan. The immediate area is characterized by a row of high-rise apartments sited along the lakefront, a large concentration of old coal or oil fired low-rise, six flat apartment buildings and a single major source - the University of Chicago steam plant. TAM 4 is approximately 5 miles southeast of Chicago's central industrial-utility complex. As indicated in Table 2.1, the frequency of high, recorded SO_2 concentrations at TAM 4 is second only to that of TAM 3. Statistical analysis of TAM 4 air quality data has indicated that the air quality in this area is very strongly correlated with ambient temperature - a finding which is consistent with the likelihood that the Hyde Park area is largely self-polluted by local, residential space heating sources.

TAM Station 5

TAM 5 is sited approximately six miles inland in the south central sector of the city. It is approximately three miles south of the central-industrial-utility complex, and is located atop a school building in a neighborhood of low-rise apartments and single family dwellings. Residential buildings in the TAM 5 area are somewhat newer than is the case for TAM 4, and gas tends to predominate over coal and oil for space heating purposes. TAM 5 is nearer to the central industrial-utility cluster than any of the other monitoring stations; however, only a few nearby large sources are located southwest of the site. This fact, combined with the relatively low residential emissions characteristic of its immediate vicinity, results in a comparatively modest number of high SO_2 concentrations recorded at this receptor (Table 2.1).

TAM Station 6

Station 6, in the extreme southeast of the city, is sited in a residential area located approximately 5 miles west of a second large concentration of Chicago industrial and power plants. Immediately adjacent to this Chicago source-cluster is the Gary-Hammond industrial complex. Since the receptor is also located within one mile of the southwest city limits of Chicago, it is exposed to emissions from two areas for which an emission inventory is not, at present, available. According to the data presented in Table 2.1, TAM 6 is located in one of the less frequently polluted areas of the city. This conclusion is consistent with the fact that the metropolitan region southwest of the city is relatively free of large SO_2 sources, and that east winds, which would bring in SO_2 from the south Chicago-Gary-Hammond area are comparatively infrequent in the midwest Great Lakes region.

TAM Station 7

TAM 7 is sited atop a school building located within 0.5 miles of the western city limits and almost 7 miles directly west of the central business district. The immediate neighborhood is predominantly residential, although a few large industrial plants are located within two miles of the receptor in the northeast and southwest directions. The staion is approximately six miles northwest of the central industrial-utility cluster.

A detailed emission inventory for the regions immediately west and south of this receptor is not now available, since these areas lie outside the Chicago city limits It is, however, known that the area west of TAM 7 is a mixed residential, light-industrial sector in which gas heating predominates, while the highly industrialized city of Cicero, Illinois, lies immediately south of TAM 7, within 2 miles of the receptor.

Although the relative scarcity of southeasterly winds minimizes the influence of the central Chicago source cluster on TAM 7, the area experiences significant SO_2 concentrations with moderately high frequency, making it the third or fourth most frequently polluted site.

TAM Station 8

Like the TAM 6 receptor, TAM 8 is located in a residential neighborhood near one of the southwestern extremities of Chicago's irregular western border. Two relatively large industrial plants lie within one mile to the northeast of the site; however, the area is relatively free of significant SO_2 sources. Since the western city limits are within 0.5 miles and the southern city limits are within one mile, emission data for virtually the entire southwestern quadrant, relative to TAM 8, are not available.

As indicated in Table 2.1, the TAM 8 receptor is sited in one of the least polluted areas of the city.

2.2 Power Plants

Electric power for the Northern Illinois region is provided by a network of 15 power generating stations. Of these, six are located in the Chicago metropolitan area. These six coal fired plants, which are shown in Figure 2.1, account for approximately 65% of the sulfur oxides released into the Chicago atmosphere. The following table indicates the relative contribution of each plant in terms of its annual fuel consumption.

Plant Designation	SO_2 Tons per Year	SO_2 Percent of City Total
Crawford	107,954	18.97
Ridgeland	100,540	17.67
Fisk	73,438	12.90
State Line	70,606	12.42
Northwest	10,566	1.86
Calumet	10,016	1.76
	373,120 Tons	65.58%

Of these installations, four: the Fisk, Crawford, Ridgeland, and State Line plants are capable of partial or total conversion from coal to natural gas during periods when the latter fuel is available at "dump or interruptible" rates.

Because of the extremely large emission rates associated with the urban power plants and because of their complex, but relatively consistent diurnal emission cycle, the acquisition of the most accurate body of emission data that could be obtained was a priority task element of the emission inventory.

Fortunately, the Chicago utility maintains excellent records of plant operation. These were provided for the period January 1966 through December 1967. The data array required was:

1) Hourly power generation, in megawatts (Mw), for each generator unit of each power plant, including an indication of whether the power was generated with coal or gas.

2) Monthly coal and natural gas consumption rates for each boiler-generator combination.

3) Monthly average coal sulfur content analyses for each plant.

4) A set of boiler-turbine-generator efficiency curves for each generator unit. These presented efficiency vs power output for each unit.

5) A set of stack temperature temperature vs output curves for each plant.

6) A physical description of each plant layout, including the relationship between boilers, turbines, generators, and stacks, stack heights, etc.

The above information was combined in a computer algorithm which yielded a calculation of the hourly fuel consumption, and SO_2 emission rates for each stack of each plant of the system. Details of the computational procedure are provided in the program progress reports (Croke, et al, 1968).

The resultant body of power plant emission data was stored in the master data file of the Air Pollution Information and Computation System (APICS) from which it could be retrieved and automatically input to the dispersion model.

The details of the APICS system are described by Kennedy and Anderson, 1969, and in the program progress reports (Croke, et al, 1968, 1969).

.3 Industrial Sources

There are over 2500 relatively large coal and oil burning industrial plants in the City of Chicago. These are responsible for approximately 10% of the sulfur oxides emitted within the city limits, on an annual average basis. The largest 100 of these plants account for over 83% of the total industrial emissions, and the largest 50 plants account for over 77% of this total.

The inventory of industrial emissions was derived from four sources. These are:

1) Department of Air Pollution Control Survey

A comprehensive annual average inventory compiled in 1963 by the Chicago Department of Air Pollution Control was computer processed to establish industrial SO_2 emissions on a square mile basis. Within any given square mile sector, industrial emissions were assumed to be uniformly distributed.

2) Argonne National Laboratory Field Survey

Detailed fuel consumption and physical and operating cycle data for the 50 largest SO_2 sources were obtained through a field survey system designed by Argonne and implemented by Laboratory and city engineers. This involved a program of site visitations and personal or telephone interviews with plant personnel.

3) Natural Gas Utility Records

The natural gas consumption records for 1966-67 and fuel costs for all dual fuel plants among the 50 largest SO_2 sources were obtained from the local, natural gas supply utility.

4) Fuel Supply Records

The Midwest Coal Producers' Institute, an organization of wholesale coal suppliers, provided records of the annual average coal consumption by major industrial sources during 1966-67.

Industrial sources that were not sufficiently large to be included among the largest 50 emitters were aggregated into uniformly distributed square mile area sources. All plants in this category were assumed to have a stack height of 150 feet.

Industrial Source Simulation Program

The 50 largest sources of SO_2 were treated as individual point sources. A detailed analysis of the diurnal, weekly, and seasonal operating pattern of each of these plants, in combination with fuel consumption records, gas use patterns, and such characteristics as process vs space heating fuel use practices was employed in an industrial plant emission simulation computer algorithm (PLANTSIM) to generate an operating shift oriented emission estimate for each plant.

The data file for large industrial sources is designed to include enough information about each plant to characterize its "expected" emission pattern by operating shift for each day throughout the year. For this purpose "shifts" are defined as follows:

Shift 1: 12 midnight to 8 am (0000) to (0800)
Shift 2: 8 am to 4 pm (0800) to (1600)
Shift 3: 4 pm to 12 midnight (1600) to (2400)

Up to three daily emission patterns may be assigned to each plant. These are as follows:

1) W - weekday or normal operation;
2) S - Saturday;
3) H - Sunday or special holidays.

Finally, a monthly weighting is provided to allow for variation due to seasonal patterns, etc. Each plant requires two computer cards; (1) a source identification card, and (2) a source emission card. Formats and an example of each are shown in Figures 2.4 and 2.5, respectively. A description of each item on the cards is provided in the following tables (Table 2.2 and Table 2.3).

It is important to note that the PLANTSIM code is completely general, in that large, individual space heating sources or major institutional sources such as coal fired water pumping stations can be treated in exactly the same manner as industrial plants. In the case of heating plants, the process load portion of the operating cycle input is zeroed and emissions are calculated solely on the basis of temperature. A special purpose plant such as a pumping station may be treated as an industrial plant which consumes fuel according to a characteristic processing cycle. Individual power plants which have a repeatable diurnal operating cycle may also be simulated by PLANTSIM; however, power plants which are a part of a regional power grid may not have a consistent and repeatable emission pattern, since such plants are likely to engage in power load transfer among plants - on at least a seasonal, if not a weekly or diurnal basis.

All sources treated in PLANTSIM are assigned individual physical stack heights based on the field survey data.

SOURCE NO.	NAME (125 CHARACTERS MAX INCL. BLANKS)	TYPE	GRID	COORDINATES		STACK DATA								WORK SCHEDULE						
				x	y	1		2		3		4								
						HGT.	%	HGT.	%	HGT	%	HGT	%	M	T	W	T	F	S	S
1 3	5 29	31 34	36 39	41 45	46 50	52 54	55 56	57 59	60 61	62 64	65 66	67 69	70 71	73	74	75	76	77	78	79
2	CAMPBELL SOUP 2550 WEST 35 STREET	2032	0809	8.2	-3.5	175	25	175	25	250	50			W	W	W	W	W	S	H

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Fig. 2.4 Source Identification Card

SOURCE NO.	MAXIMUM SPACE HTG. LOAD (THERM/hr)	MAXIMUM PROCESS LOAD (THERM/hr)	MONTHLY FUEL USE WEIGHTING (% OF MAXIMUM PROCESS)												SHIFT FUEL WEIGHTING (% OF MONTHLY PROCESS)									% SULPHUR COAL	AVG. % COAL	% SULPHUR OIL	AVG. % OIL	% GAS SP. HTG	% GAS PROCESS	AVG. TEMP. GAS (°F)	GAS PRICE (¢/THERM)
			J	F	M	A	M	J	J	A	S	O	N	D	W			S			H										
															1	2	3	1	2	3	1	2	3								
1 3	5 9	11 15	17	18	19	20	21	22	23	24	25	26	27	28	30 31	32 33	34 35	36 37	38 39	40 41	42 43	44 45	46 47	49 51	53 55	57 59	61 63	65 67	68 70	72 73	75 79
2	500	5000	6	6	6	5	5	4	2	4	6	7	6	6	70	99	99	70	20	20	30	30	30	2.8	100			100	100	40	0.042

113-2864-T-1

Fig. 2.5 Source Emission Card

TABLE 2.2. SOURCE I.D. CARD

NO.	ITEM	DESCRIPTION
1	SOURCE NO.	Plant sequence number
2	NAME	Plant name (not to exceed 25 characters including blanks), address may be included if sufficient space is available
3	TYPE	Standard industrial code
4	GRID	City of Chicago square mile number
5	COORDINATES	x and y coordinates relative to standard City of Chicago coordinate system
6	STACK DATA	Four stacks maximum (1, 2, 3, 4) HGT - Stack height in feet % - The percent of total emission emitted from each stack
7	WORK SCHEDULE	Each day of the week is assigned to one of the following patterns: i) W - Weekday ii) S - Saturday iii) H - Sunday or Holiday

TABLE 2.3. SOURCE EMISSION CARD

NO.	ITEM	DESCRIPTION
1	SOURCE NO.	Plant sequence number
2	MAX SPACE HTG LOAD	Maximum hourly thermal requirements for space heating
3	MAX PROCESS LOAD	Maximum hourly thermal requirements for process
4	MONTHLY FUEL USE WEIGHTING	Achieves monthly variation in process fuel use. Each month is assigned a weight (0, 1, ..., 9) which corresponds to the average percent (0%, 10%, ..., 90%) of maximum process fuel that is used during that month.
5	SHIFT FUEL USE WEIGHTING	Within each daily pattern (W, S, H), a weight (0%, ..., 99%) is assigned to each shift which corresponds to the average percent of current monthly process fuel that is used during that shift
6	% SULFUR COAL	Average percent of sulfur in coal
7	AVG % COAL	Average percent of thermal load due to coal (0 implies coal is not used)
8	% SULFUR OIL	Average percent of sulfur in oil
9	AVG % OIL	Average percent of thermal load due to oil (0 implies oil is not used)
10	% GAS SP HTG	The percent of space heating thermal requirements that can be supplied by gas
11	% GAS PROCESS	The percent of process thermal requirements that can be supplied by gas
12	AVG GAS TEMP	The average ambient temperature (°F) at which the dual fuel plant receives gas on an "interruptible" supply contract
13	GAS PRICE	The gas rate (¢/Therm) for dual fuel plants

PLANTSIM Computations

When the temperature, T, is between -10°F and 55°F, a linear relationship for the space heating thermal load L^S is assumed. This is expressed as follows:

$$L^S = L^S_{MAX} \frac{[55 - T]}{65} \quad (-10 \leq T \leq 55) \qquad (2.1)$$

Then the total thermal load is

$$L = L^S + L^P , \qquad (2.2)$$

where L^P, the process load, is determined from the appropriate month, day, and shift factors. The amount of load due to coal, L^C, and due to oil L^O, is then determined, and the SO_2 emission due to each source is calculated as follows:

1. $$C(\text{tons/hour}) = \frac{L^C(\text{TH/Hour}) \times 10^5(\text{Btu/TH})}{12000(\text{Btu/lb}) \times 2000(\text{lbs/Ton})}$$

$$SO_2^C(\text{lb/Hour}) = C(\text{Tons/Hour}) \times 36.8 \times \%S^C$$

2. $$O(\text{kgal/Hour}) = \frac{L^O(\text{Th/Hour}) \times 10^5(\text{Btu/TH})}{18000(\text{Btu/lb}) \times 8000(\text{lbs/kgal})}$$

$$SO_2^O(\text{lb/Hour}) = O(\text{kgal/Hour}) \times 157.0 \times \%S^O$$

Thus, the total SO_2 emission is

$$SO_2 = SO_2^C + SO_2^O \qquad (2.3)$$

When the ambient temperature is such that a dual fuel interruptible plant is probably receiving natural gas, the amount of SO_2 produced is correspondingly reduced.

In order to facilitate data storage according to a uniform and consistent format, each plant is assumed to have four stacks. For plants having less than four stacks, zeros are filled in for non-existent stacks. The following parameters are associated with each stack:

1. SO_2 emission in lbs per hour
2. Heat emission in therms per hour.

These parameters are determined by weighting the total SO_2 and heat emissions for the plant by the percentage emitted from each stack. The heat emission, H, is assumed to be 15% of the thermal input.

Example

Consider the example of the Campbell Soup Company shown in Figs 2. and 2. and assume that emission data are required for the following set of conditions:

1. January
2. temperature 30°F
3. weekday pattern
4. first shift.

Then,

$$L^S = \left[500 \frac{55 - 30}{65}\right] = 200 \text{ TH/Hr}$$

$$L^P = (.70)(.60)5000 = 2100 \text{ TH/Hr}$$

$$L = 2300 \text{ TH/Hr}$$

$$L^C = 2300 \text{ TH/Hr}$$

$$L^O = 0$$

$$C = \frac{2300 \times 10^5}{12000 \times 2000} \cong 10 \text{ Tons/Hr}$$

$$SO_2 = 10 \times 36.8 \times 2.8 = 1000 \text{ lbs/Hr}$$

$$H = (.15)2300 = 345 \text{ TH/Hr}$$

For Stack 1

$$SO_2^{(1)} = (.25)1000 = 250 \text{ lbs/Hr}$$

$$H^{(1)} = (.25)345 = 85 \text{ TH/Hr}$$

For Stack 2

$$SO_2^{(2)} = (.25)1000 = 250 \text{ lbs/Hr}$$

$$H^{(2)} = (.25)345 = 85 \text{ TH/Hr}$$

For Stack 3

$$SO_2^{(3)} = (.50)1000 = 500 \text{ lbs/Hr}$$

$$H^{(3)} = (.50)345 = 170 \text{ TH/Hr}$$

For Stack 4

$$SO_2^{(4)} = 0$$

$$H^{(4)} = 0$$

2.4 Residential Space Heating Sources

Residential space heating sources account for approximately 15% of the annual total emissions for the city. The inventory of coal and oil fired residential space heating sources was derived primarily from data supplied by the market research organization of the local natural gas supply utility. This information was in the form of a city-wide, field sampling survey of space heating sources categorized by fuel use and by the number of dwelling units per building surveyed. For the purposes of the emission inventory, the survey data was aggregated into two groups - moderate sized residential structures of 19 dwelling units or less and large apartment complexes of 20 or more dwelling units.

Since residential sources are generally too small and too numerous to treat individually, the two building size categories described above were treated as uniformly distributed square mile area sources. The source density per square mile for each category was assigned on the basis of the natural gas utility market research data.

The operating cycle of the moderate sized heating plants was based on a 55°F degree day proration of a seasonal average fuel consumption modified by an empirical function which represents the daily cycle of automatic stoking during waking periods followed by a hold-fire and cooldown during sleeping periods. This cycle was simulated by a "Janitor Function" which maintains heating sources on an automatic stoking cycle between 6 AM and 11 PM on days having a minimum night ambient temperature in excess of 5°F. For nights with a minimum temperature below 5°F, the automatic stoking period was assumed to begin at 3 AM. This pattern was derived through an interview survey of building superintendents and

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[*] (Croke, et al, 1968)

heating plant operators. A hot water heating baseload equal to 10% of the daily heating fuel use was assumed for all residential buildings in this category. Hourly average emissions were assumed to be distributed uniformly throughout the automatic stoking period and were assumed to be constant during the hold-fire period. All moderate sized residences were assigned a uniform physical stack height of 50 feet.

Large residential buildings were considered to operate on an automatic stoking cycle at all times. Fuel use and SO_2 emissions were based on a 55°F degree day proration and a hot water heating baseload equal to 10% of the daily heating fuel use was assumed. All buildings in this size category were assumed to have a 200 foot physical stack height - an assumption based on a sensitivity analysis of the effect of stack height on the ground level air quality, and on surveys of actual building sizes.

The hourly average emissions for large size residential buildings were assumed to be distributed uniformly throughout the stoking period.

Commercial and Institutional Sources

Commercial and institutional sources account for about 8% of the total emissions in Chicago. Fuel use and SO_2 emission data for large commercial and institutional sources such as office buildings, water pumping stations, educational institutions, etc., were derived from a computer analysis of a comprehensive inventory developed in 1963 by the Chicago Department of Air Pollution Control, combined with the results of a field survey of major sources conducted in 1968 by Argonne National Laboratory and the Department of Air Pollution Control.

With a few notable exceptions, the commercial and institutional sources are too small and numerous to treat individually. They are therefore aggregated as area sources, uniformly distributed throughout each square mile of the city. The square mile source density is based on the 1963 inventory.

Virtually all sources in this category burn fuel primarily for space and hot water heating and operate on an automatic stoking cycle. Emissions from these sources were therefore calculated in exactly the same way as in the case of the large residential sources.

Certain commercial and institutional plants are sufficiently large to warrant inclusion as individual point sources. Among these are the five Chicago pumping stations and a number of space heating plants which are associated with extremely large buildings. An operational analysis of the pumping stations was conducted in order to define their diurnal emission cycle. They were then treated in essentially the same manner as the large industrial plants. Individual large commercial heating plants were treated in a manner similar to the large residential structures. The validity of the latter assumption was established through a detailed survey of the operating cycles of most of these sources, which included the large University of Chicago heating plant, the Union Station, the Chicago Merchandise Mart, the Chicago Housing Authority complexes, etc.

3.0 Meteorological and Air Quality Data

3.1 Chicago's TAM Network

In January 1966, The Chicago Department of Air Pollution Control began recording wind speed and direction and sulfur dioxide levels at eight telemetered air monitoring (TAM) stations (starred locations on the map, Fig 2.1). These continuous measurements are integrated over 5-minute periods; 15-minute averages are then telemetered to the DAPC office where they are recorded. Tape records of these 15-minute observations have been edited and formed into hourly averages. Thus, while the accuracy of data from some of the aerovane sites is compromised by 15-30 foot masts and/or close proximity to taller buildings or smoke stacks, the procedure for developing hourly averages is excellent. This is in contrast to special airport data where the aerovane sites are excellent, but only brief observations at the hour are recorded.

In the dispersion model, the wind speed and wind direction from the TAM aerovane nearest to the dose point is used to determine the trajectory of all plumes sensed at that point. This temporary assumption will eventually be eliminated by using all eight stations to develop a wind field for the city. In contrast to single citywide values of wind speed and direction from the nearest airport, the data from a local aerovane is sensitive to special circulation patterns such as lake breezes.

3.2 Airport Data

Tapes containing standard weather hourly data from Midway Airport and Glenview Airport (15 miles north of Chicago) have been obtained from the National Weather Records Center.

3.3 Argonne Meteorological Data

The observing station at Argonne National Laboratory (25 miles southwest of Chicago) was specifically designed to measure those parameters controlling diffusion: atmospheric stability, wind speed and direction at five levels up to 150 feet, net and solar radiation, etc. Hourly averages are stored on magnetic tape. These are the only stability records available in the Chicago area. Unfortunately, the data are for a shallow layer and are taken in an open, grass covered field. Studies are underway relating these data to the urban environment.

3.4 Upper Air Data

Radiosonde observations from the U.S. Weather Bureau RAWIN station at Peoria, Illinois (140 miles southwest of Chicago) and Green Bay, Wisconsin (180 miles north of Chicago) have been obtained from the National Weather Records Center. These data have been extrapolated to estimate the height of the mixing layer in Chicago (see Section 3.6).

3.5 Atmospheric Stability

Turbulent diffusion of pollutant species is represented in the model by a Gaussian puff kernel with dispersion coefficients $\sigma_{x_i}(T)$, $\sigma_{y_i}(T)$, $\sigma_{z_i}(T)$; where T is the travel time and i the atmospheric stability index. The classification system proposed by Turner (1963) has been employed using weather data from Midway Airport.

3.6 Height of the Mixing Layer

The mixing layer defines a zone within which pollutants can be diluted. The height of this layer is probably the most critical parameter in determining ground level SO_2 concentrations resulting from emissions from tall stacks. With a high lid (> 2000 feet) plumes from power plants tend to travel far and disperse widely before touching ground. With a sharp temperature inversion beneath the physical stack height, plumes will travel in stable air which greatly inhibits vertical diffusion and therefore touch ground far from the local urban area. High ground level concentrations occur in the intermediate range of mixing layer heights where the plumes are trapped beneath the lid and disperse rapidly to ground in unstable air. Figures 3.1 and 3.2 show vertical profiles of temperature and sulfur dioxide as measured by an instrumented helicopter at a point four miles downwind of a major industrial area in Chicago. The sharp inversion at 2300 feet (700 meters) has clearly defined a vertical mixing zone within which SO_2 levels are nearly uniform.

Other than the low level rural temperature profiles measured at Argonne, no vertical soundings are available for the Chicago area during the period from January 1966 when the TAM network became operational to January 1969. This is the period during which meteorological air quality and emission data have been accumulated at Argonne. It was therefore necessary to design a scheme for estimating the height of the mixing layer from historical weather data. (In July 1969 the E.S.S.A. service bureau for the Chicago Air Quality Control Region began a program of daily balloon sounding at 0600 and 1200 from Midway Airport. This data will be available for future validation studies of the dispersion model and will also be used to validate the objective mixing layer height estimate described in this section.)

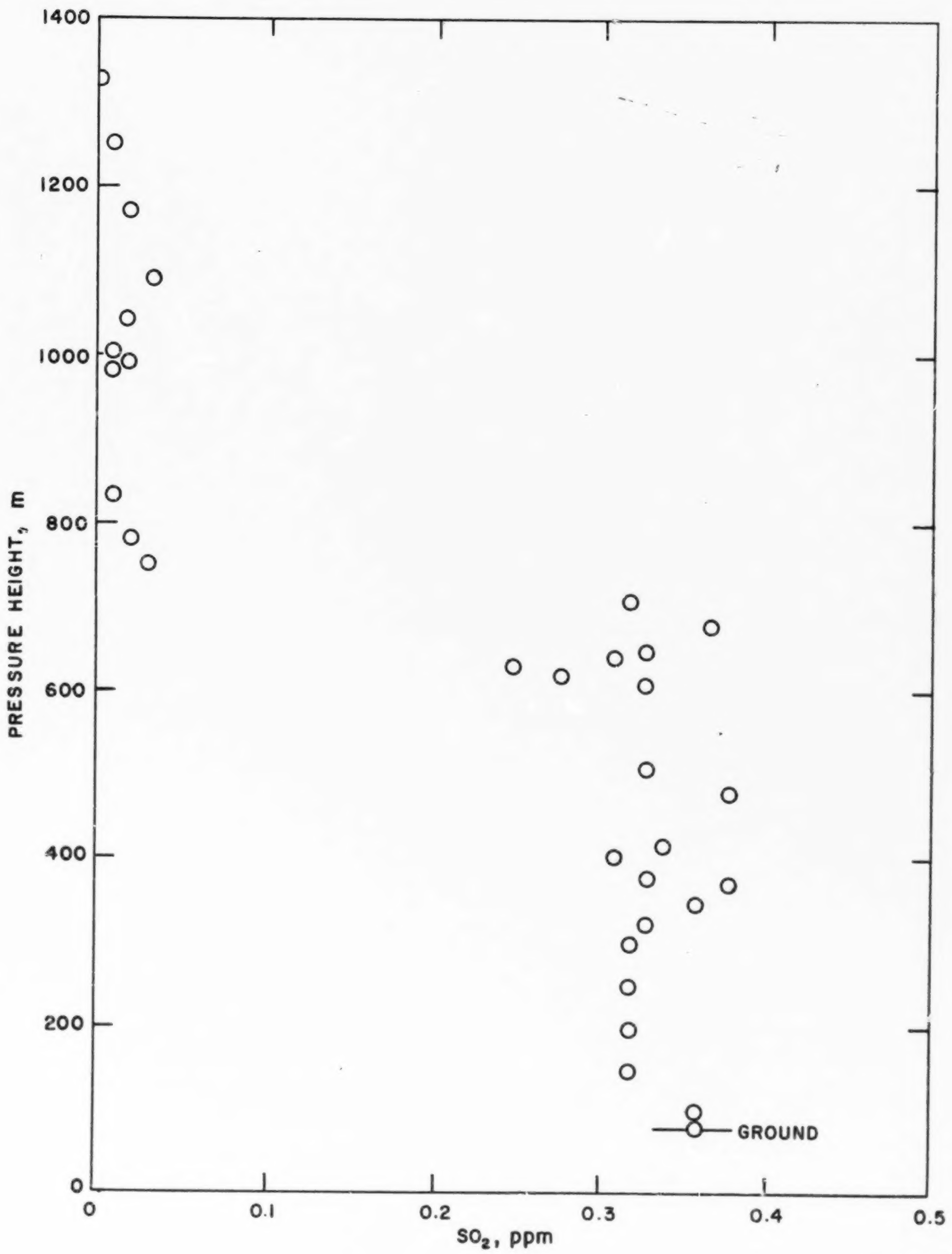

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Fig. 3.1 Vertical Profile of SO_2 Hinsdale, Illinois April 11, 1969, 10:20 A.M. (D. Nelson, Argonne National Laboratory).

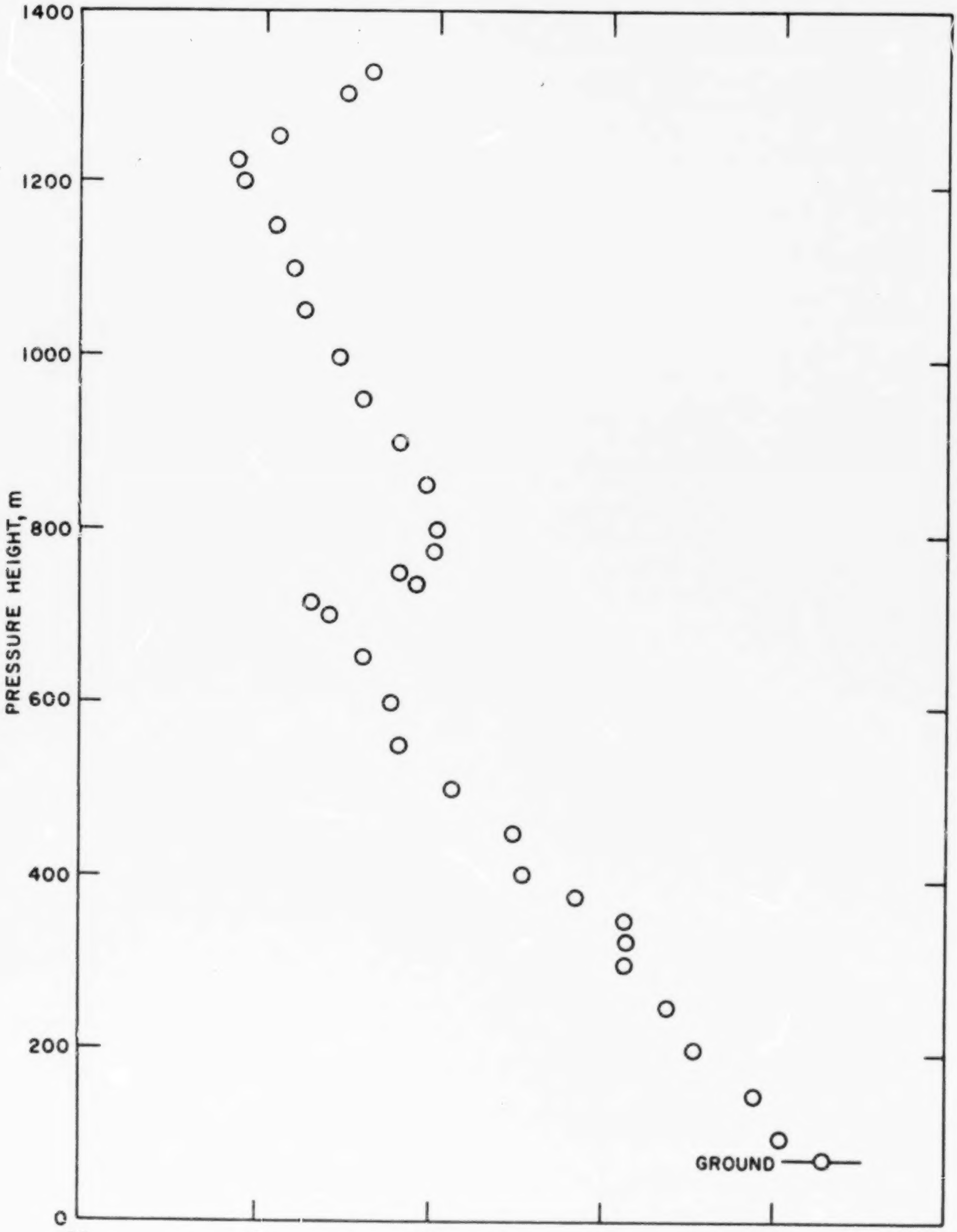

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Fig. 3.2 Vertical Profile of Temperature Hinsdale, Illinois April 11, 1969, 10:20 A.M. (D. Nelson, Argonne National Laboratory).

The computerized objective mixing layer depth estimates are based on an interpolation scheme between two rawinsonde stations, Green Bay, Wisconsin, and Peoria, Illinois. The soundings are usually taken at 0600 and 1800 CST. The mandatory and significant levels for each station are merged to form a single pressure-temperature array for each sounding. The Chicago rural (Argonne) temperature profile is formed either by "shifting" one of the two to the Argonne surface temperature or by interpolation between the Peoria and Green Bay soundings. If only one station was in the same air mass as Chicago, the sounding from that station is transposed, without changing its shape, to the Argonne surface temperature at sounding time. If both Peoria and Green Bay were in the same air mass as Chicago (as determined by inspection of the daily weather map), then a linear interpolation is performed. This procedure forms a pressure-temperature array for the 0600 and 1800 rural profiles.

The next step is to compute the hourly rural profiles using temporal weighting. The profile for any hour is linear interpolation in time between the bracketing 0600 and 1800 rural soundings.

The hourly urban mixing depth and mixing depth indices are now computed. The height of the mixing layer is defined by the intersection of a dry adiabat from the urban surface temperature with the constructed Argonne rural temperature profile. Mixing layer heights calculated by this objective procedure were compared with more subjective estimates provided by a local meteorological consulting firm. While actual magnitudes differed, there was good agreement in terms of diurnal trends. Calculated values agreed very closely with data from two helicopter soundings but, in both cases, the inversions were above 2000 feet and therefore not in the critical range where plume trapping can occur.

4.0 Transport of Airborne Pollutants

Pollution concentrations from a given source are evaluated in this model by forming a convolution sum of two time series: (1) piecewise (hourly) constant stack emissions and (2) a discrete transfer function based on the mathematical representation of an integrated puff. The latter is found by integration of a Gaussian kernel representing advection according to a time series of piecewise constant wind vectors and three-dimensional dispersion according to a time series of piecewise constant classes of atmospheric stability. For example, results indicate that one of the more important types of short term pollution incidents, the morning fumigation, which is characterized by low winds (up to 6 mph) and by a sharp transition from stable stratification to strong vertical mixing, is simulated successfully. Details of the development of the kernel and limitations on its range of applicability are discussed in the following sections.

Dispersion Kernel

For a steady mean wind U in the downwind (x) direction with y and z representing unbounded crosswind and vertical dimensions, a normal distribution yields the following Green's Function:

$$\frac{X(t,t')}{Q(t')} = \frac{\exp -\left\{\frac{[x - U(t-t')]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right\}}{(2\pi)^{3/2}\sigma_x(t-t')\sigma_y(t-t')\sigma_z(t-t')} \qquad (4.1)$$

where $X(t,t')$ is the concentration at time, t, due to an instantaneous release Q at time t' and position (0,0,0) (Pasquill, 1962; Slade 1966). The dispersion coefficients σ_x, σ_y, σ_z are assumed to be functions only of the delay time $T = t - t'$ and the atmospheric stability class (Turner, 1964).

Assume Q(t) piecewise constant over a fundamental time interval Δ (e.g., Δ = 1 hour); then, for the special case of a steady wind in the x-direction, the concentration $X(x,y,z,m)$ at time $t = m\Delta$ can be found by a convolution of the piecewise constant emissions with a series of integrals (the discrete transfer function) evaluated over periods of duration Δ:

$$X(x,y,z,m) = \sum_{n=1}^{m} Q_{m-n+1} \int_{(n-1)\Delta}^{n\Delta} \frac{\exp - \left\{ \frac{(x-UT^2)}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} \right\}}{(2\pi)^{3/2}\sigma_x(T)\sigma_y(T)\sigma_z(T)} \, dT \qquad (4.2)$$

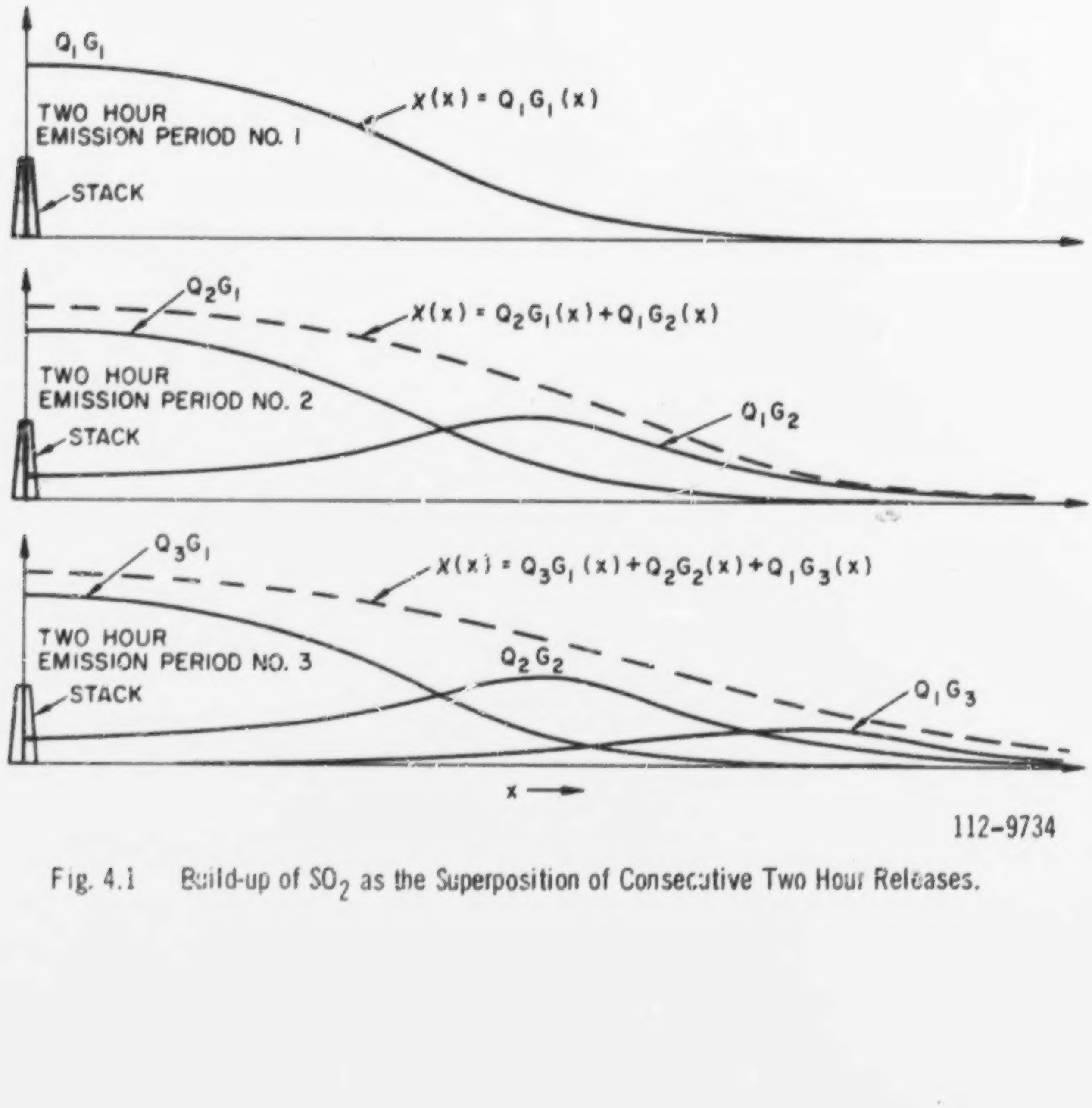
$$= \sum_{n=1}^{m} Q_{m-n+1} G_n$$

This is represented schematically in Fig 4.1 by the buildup of SO_2 due to three ($m = 3$) consecutive two hour ($\Delta = 2$) piecewise constant emissions.

Equation 4.2, the contribution from an individual source to the concentration at time $m\Delta$, must then be summed over all sources.

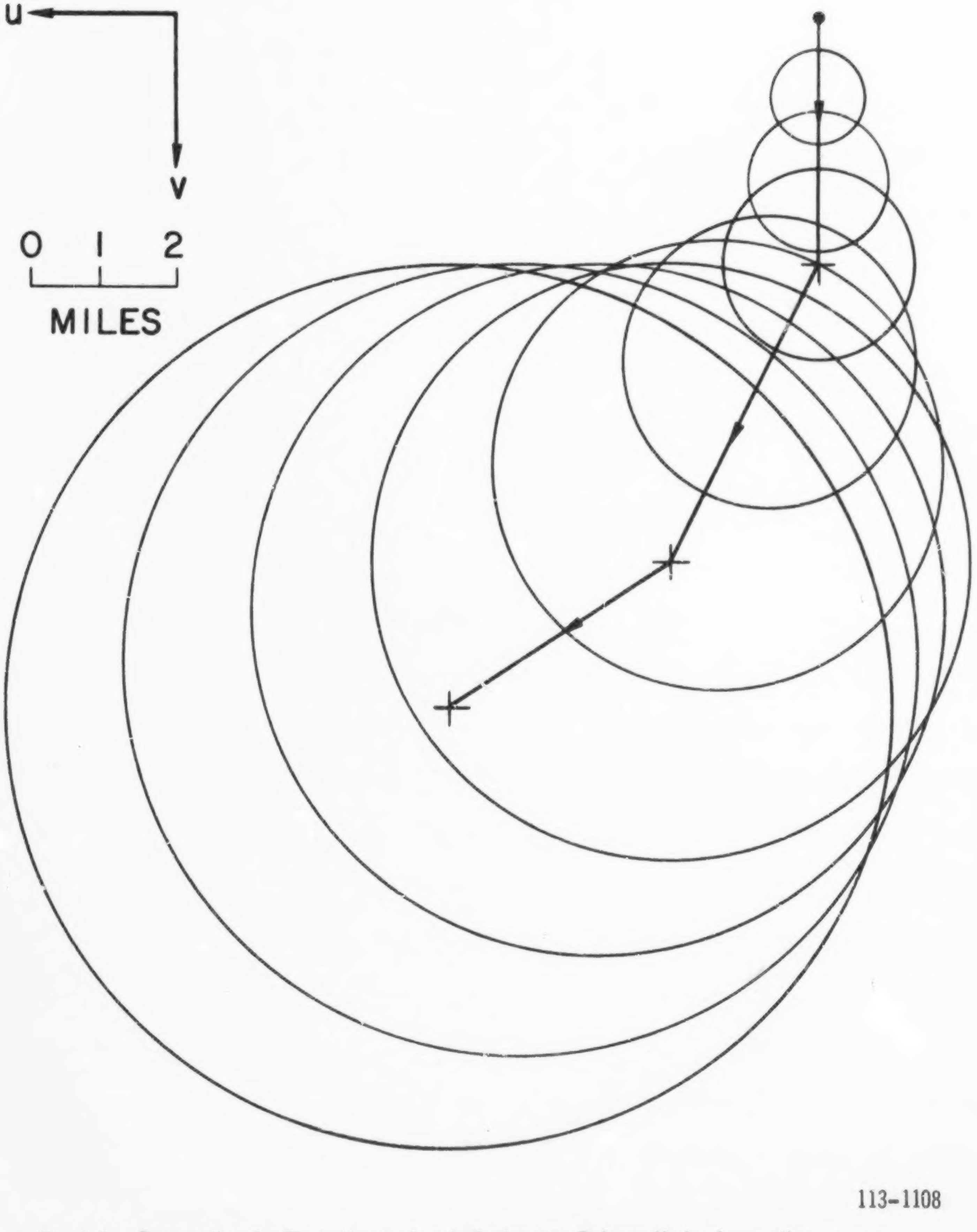
Equation 4.2 can be generalized to account for variation (piecewise constant) in wind direction, wind speed, and atmospheric stability:

$$G_{m,n} = \int_{(n-1)\Delta}^{n\Delta} dT \, \frac{\exp - \left\{ \begin{array}{l} [x - \Delta \sum\limits_{j=m-n+2}^{m} u_j - u_{m-n+1}(T-\Delta(n-1))]^2/2\sigma_h^2(T) \\ + \; [y - \Delta \sum\limits_{j=m-n+2}^{m} v_j - v_{m-n+1}(T-\Delta(n-1))]^2/2\sigma_h^2(T) \\ + \; z^2/2\sigma_z^2(T) \end{array} \right\}}{(2\pi)^{3/2}\sigma_h^2(T)\sigma_z(T)} \qquad (4.3)$$


Q1 G1
χ(x) = Q1 G1 (x)
TWO HOUR
EMISSION PERIOD NO. 1
STACK
Q2G1
χ(x) = Q2G1(x)+Q1G2(x)
TWO HOUR
EMISSION PERIOD NO. 2
Q1G2
STACK
Q3G1
χ(x) = Q3G1(x)+Q2G2(x)+Q1G3(x)
TWO HOUR
EMISSION PERIOD NO. 3
Q2G2
STACK
Q1G3
x ⟶

112–9734

Fig. 4.1 Build-up of SO_2 as the Superposition of Consecutive Two Hour Releases.


u
v
0
1
2
MILES

113-1108

Fig. 4.2 Propagation for Three Hours of an Instantaneous Release Under Assumption $\sigma_x = \sigma_y$

where variations in wind velocity are represented by the piecewise constant series $[u_j]_1^m$ and $[v_j]_1^m$. Note that this result is contingent upon the assumption of $\sigma_x = \sigma_y = \sigma_h$, a horizontal dispersion coefficient. There are valid arguments (to be reviewed in a later section) why this assumption is questionable except perhaps for very low wind speeds. From a computational standpoint, the puff appears circular if $\sigma_x = \sigma_y$, and consequently, since its x,y shape is independent of wind direction, the generalization of the kernel to accommodate variations in wind direction is greatly simplified. The propagation of a circular puff for varying wind speed and direction is easily visualized by the schematic of Fig 4.2.

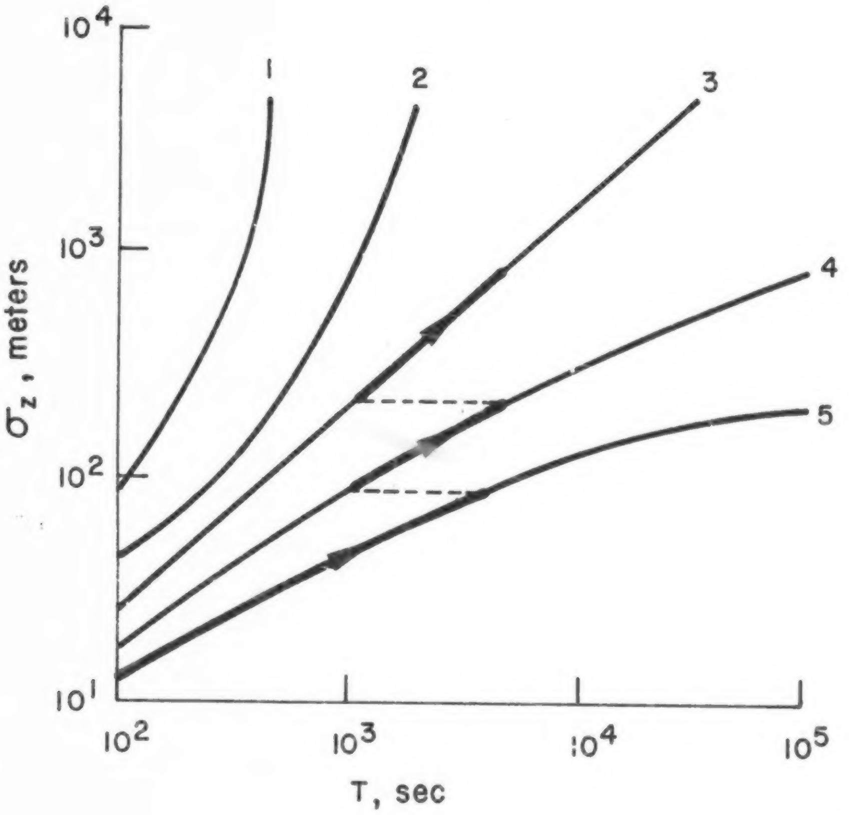
In simulating lake breezes and unusual urban circulations, continuity in the wind field and conservation of the mass of pollutant require introduction of a vertical velocity component. This component as well as the horizontal quantities u and v will be highly dependent upon space and time variations. Equation 4.3 considers only time dependence of the wind, although one can use different sequences $[u_j]_1^m$ and $[v_j]_1^m$ depending upon the location of the dose point. Using the lake breeze and, in particular, a dose point near the confluence as an example, we must allow for two converging streams and a vertical motion which is highly space dependent. The algorithms presented in this paper are not yet expressed in a sufficiently general manner to handle this space dependence. However, it seems relatively straightforward to approximate a three-dimensional velocity field by the three components $u(x,y,t)$, $v(x,v,t)$ and $w(x,y,t)$ and restate the basic algorithm.

4.2 Variable Atmospheric Stability

Postulating variations of σ with travel time T (Turner, 1964) and requiring continuity of σ at each time step, we might describe a three step process by the paths shown in Figure 4.3.

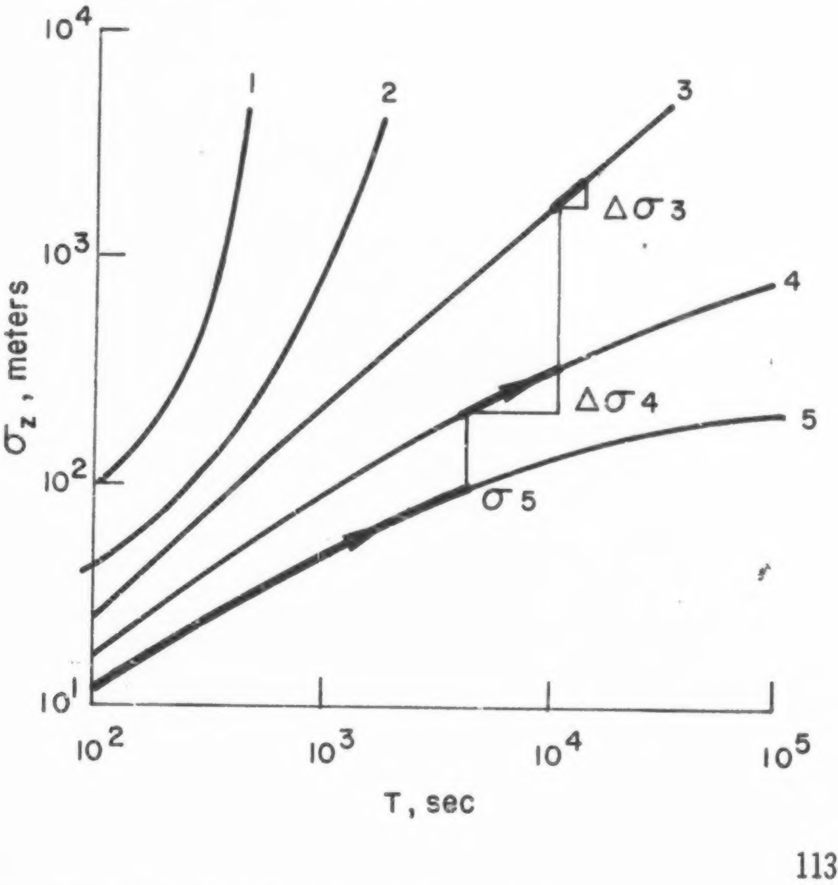
Associated with each puff are functions of time, $\sigma_h(t)$ and $\sigma_z(t)$, which could in principle be calculated according to the procedure of Figure 4.3. This procedure requires calculation of a psuedo-time for travel within each new stability class. Although the stability class does not change every hour, a computer program based on hourly steps must provide a general algorithm for handling this situation. Unfortunately, the process in Figure 4.3 appears devoid of any simple algorithm suitable for economic programming on the computer. The problem is that the dispersion coefficient σ should be kept continuous in spite of the fact that we are forced to employ a set of discrete functions.

An approximation to the "continuous σ" scheme of Figure 4.3 is proposed in Figure 4.4 for which the time of flight is continuous and the value of $\sigma(t)$ is determined by adding changes in σ. A comparatively simple algorithm can be written to implement the procedure of Figure 4.4. The two procedures are compared in Table 4.1 where it is shown that a tolerable error is incurred by the approximate method of Figure 4.4 as opposed to the "exact" method of Figure 4.3. In this comparison, a single change in stability occurs at the beginning of period 2.



113-1110

Fig. 4.3 Three Step Variations in Stability Class.
Δ = 5000 sec; σ Is Continuous



113-1109

Fig. 4.4 Three Step Variations in Stability Class.
Δ = 5000 sec; Approximate Method; T Is Continuous
$\sigma = \sigma_5 + \Delta\sigma_4 + \Delta\sigma_3$

Table 4.1 Method of Fig. 4.3 (exact) vs. Method of Fig. 4.4 (approx.)

$\Delta = 5000$ sec; σ at 10,000 sec

Stability Class		σ_y(m)		σ_z(m)	
Period 1	Period 2	"exact"	"approx."	"exact"	"approx."
4	5	2000	1900	200	230
5	4	1900	1700	200	220
3	5	2400	2500	1000	1100
5	3	2500	2100	1100	1120

4.3 Dispersion Coefficients

The integrated puff model is similar to earlier dispersion models in that a Gaussian distribution with appropriate dispersion parameters is the fundamental assumption. Although the puff model is closer to physical reality, it is still dependent and quite sensitive to these dispersion coefficients.

There are a number of sets of functions for σ_y and σ_z with either downwind distance or time of flight as the independent variable, and for the most part these curves are in mutual agreement. Some modifications (for example, by Turner (1968) in the St. Louis study) have been made to account for greater instability over a city since the various sets of curves are based on experiments over level, rural terrain. Recent field experiments in St. Louis by McElroy and Pooler (1968) support these modifications although their estimates of the coefficient of vertical diffusion may be excessive if applied to smoke plumes because their data was obtained by tracer releases at ground level.

A serious consideration is the choice of the function $\sigma_x(j,t)$ required for the integrated puff model. The results of field experiments on instantaneous and steady releases (Cramer, 1964; McElroy and Pooler, 1968) have been processed to yield dispersion coefficients which fit the plume model:

$$\chi = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp - \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} \quad . \qquad (4.4)$$

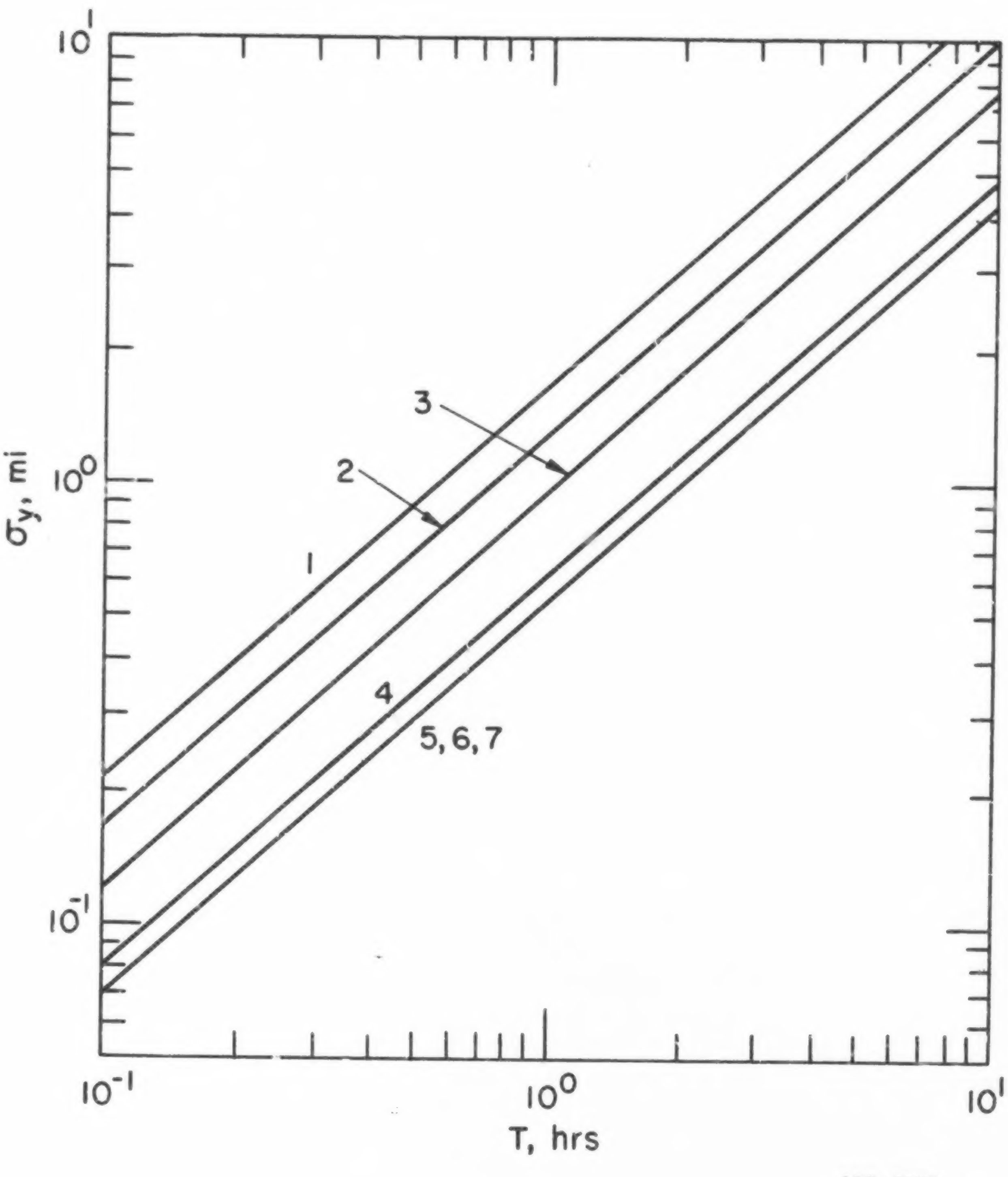
Extensive horizontal measurements were employed to determine σ_y statistically; σ_z was inferred from these. Clearly the introduction of an additional dispersion coefficient σ_x with a corresponding change in the basic equation will alter the analysis of the experiments and thus the conclusions as to the magnitude of dispersion coefficients.

Another concern is the assumption $\sigma_x = \sigma_y$ which results in the advecting/diffusing circular puff discussed in Section 4.1 and in Figure 4.2. Although not strictly correct, it is convenient to consider σ_x as the superposition of two components: (1) horizontal turbulence due to eddies of a scale smaller than the puff size, and (2) upwind/downwind elongation due to vertical shear. Thus, while the assumption $\sigma_x = \sigma_y$ may be reasonable for unstable and neutral conditions of atmospheric stability, it may be inappropriate in situations where the effect of wind shear is magnified by the existence of a stable atmosphere which inhibits vertical mixing (Bowden, 1965; Cramer, 1968). However, in these cases, smoke plumes from major emitters will probably not touch ground within the urban area.

The dispersion coefficients used to obtain the results presented here obey the sets of functions $\sigma_{y,i}(t)$, $\sigma_{z,i}(t)$, $i = 1,5$ proposed by Turner (1968) for use in his St. Louis Model (Figures 4.5 and 4.6). Furthermore, it is assumed that $\sigma_x = \sigma_y$.

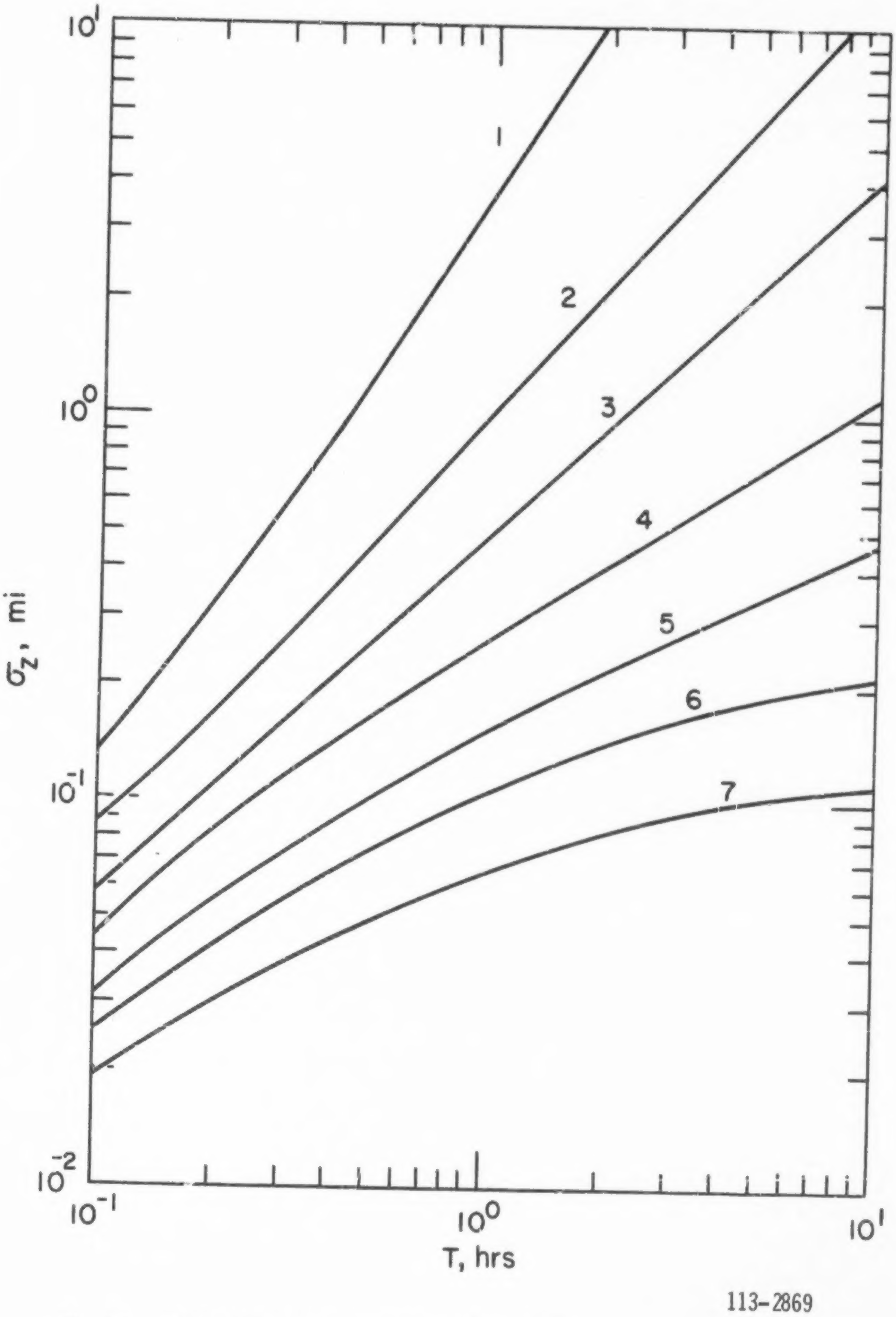
4.4 Plume vs Puff Calculations

Equation 4.2, which for constant Q expresses the steady state concentration according to the integrated puff formulation, will in general not agree with the plume equation (4.4) evaluated at $T = x/u$. However, on the centerline ($y = 0$, $z = 0$) the two equations yield almost identical results for u _ 1 mph.



113–2876

Fig. 4.5 Transverse Dispersion Parameter (Turner, 1968).



113-2869

Fig. 4.6 Vertical Dispersion Parameter (Turner, 1968).

The linear plots of $\sigma_z(T)$ and $\sigma_y(T)$ (Fig 4.7, 4.8) indicate that for the first few hours of travel time, the dispersion coefficients in Figures 4.5 and 4.6 can be approximated by the linear relations: $\sigma_x = \sigma_y = \alpha T$; $\sigma_z = \gamma T$. Substitutions of these functions into Eq. 4.1 for $y = z = 0$ yields the following:

$$\chi_{℄} = Q \int_0^\infty dT \, \frac{\exp - \left\{ (x-UT)^2 / 2\sigma_x^2(T) \right\}}{(2\pi)^{3/2} \sigma_x(T) \sigma_y(T) \sigma_z(T)}$$

$$= \frac{Q}{2\pi(\alpha\bar{T})(\gamma\bar{T})U} \left\{ \frac{e^{-r^2}}{2\sqrt{\pi} r} + \frac{\mathrm{erf}(r)}{2} + \frac{1}{2} \right\} \qquad (4.5)$$

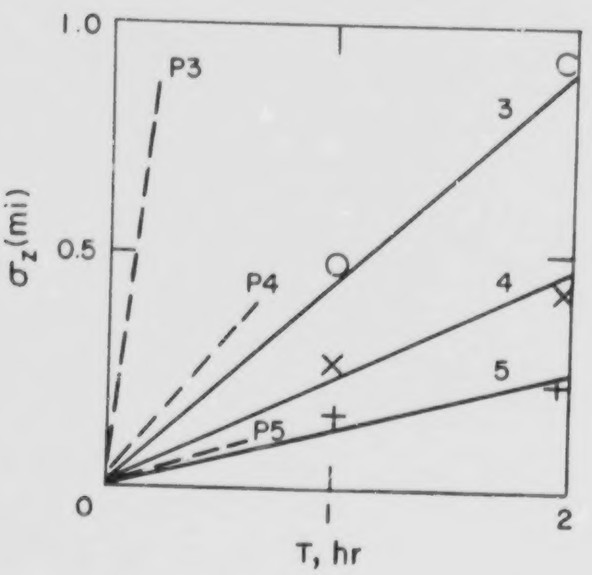
where $\bar{T} = x/U$, $r = U/(\sqrt{2}\alpha)$

and (the error function) $\mathrm{erf}(r) = \frac{2}{\sqrt{\pi}} \int_0^r e^{-t^2} dt$

Thus the integral can be evaluated as:

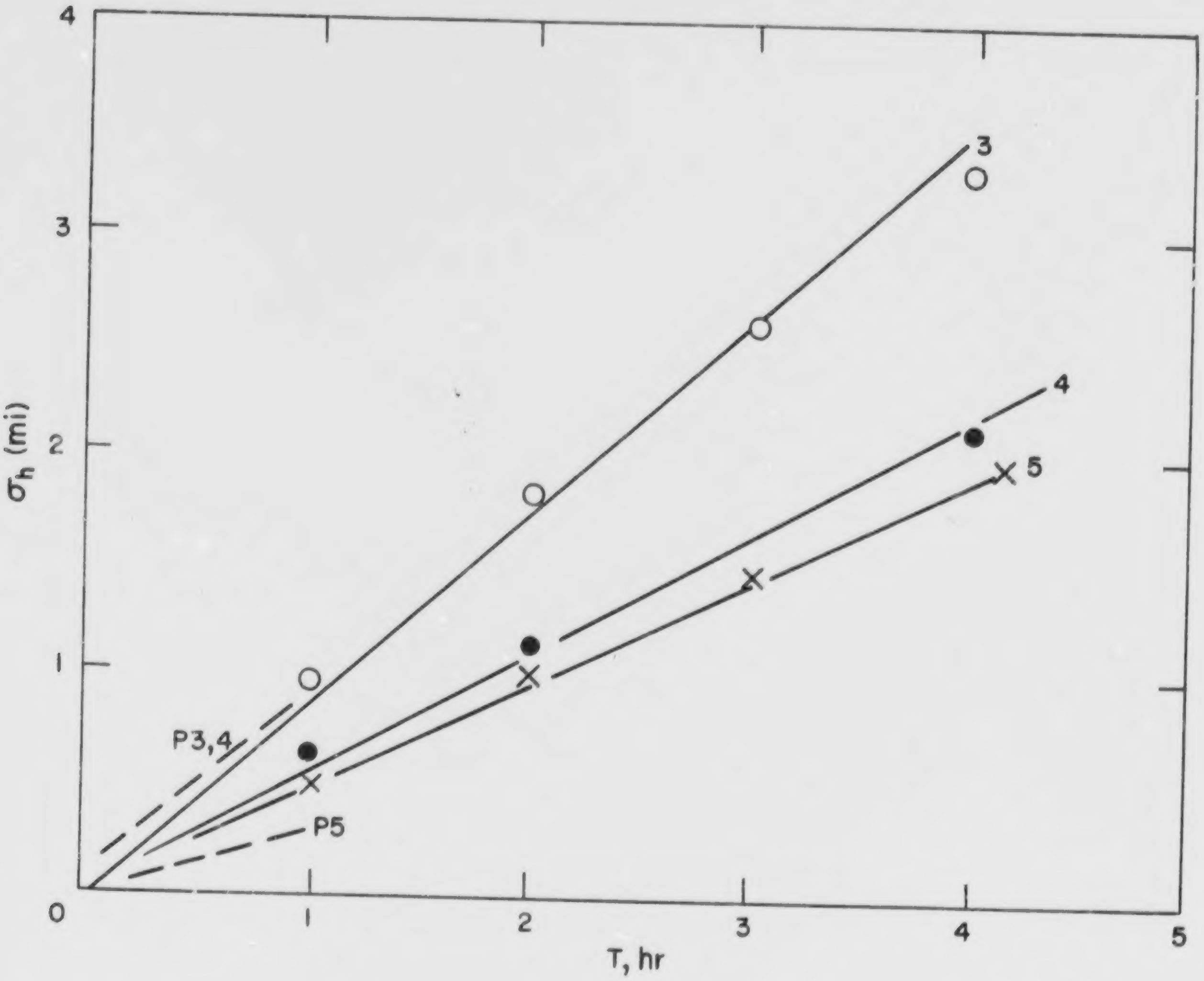
$$\chi_{℄} = PF \qquad (4.6)$$

where P, the factor outside the brackets in Eq. 4.5, is the plume equation evaluated at $\bar{T}$, the time of flight to the dose point x . The terms within the bracket, represented by the factor F, are tabulated in Table 4.2 for several values of r. For a given value of r, there is a corresponding value of α, (Fig 4.8) and thus U for each stability class $i = 3,4,5$.



113-2860-T-1

Fig. 4.7 Linear Plot of $\sigma_z(T)$ for Stability Classes 3, 4, and 5. Plots Labeled "P" Are Recent Data from St. Louis (Mc Elroy and Pooler, 1968).



113-2861-T-1

Fig. 4.8 Linear Plot of $\sigma_y(T)$ for Stability Classes 3, 4, and 5. Plots Labeled "P" Are Recent Data from St. Louis (Mc Elroy and Pooler, 1968).

2

Table 4.2

Plume vs. Integrated Puff Formulations

On the Centerline (Eq. 4.5, 4.6)

$r = U/\sqrt{2}\,\alpha$	U_3	U_4	U_5	F
10	12mph	8mph	7mph	1.00
1	1.2	.8	.7	1.03
.7	.8	.5	.4	1.10
.5	.6	.4	.3	1.22
0	0	0	0	∞

According to Table 4.2, the integrated puff calculation is 3% greater in steady state on the centerline than the plume formula for U = 1mph under unstable atmospheric conditions. Table 4.2 also indicates that the ratio of puff to plume results becomes infinite as $U \to 0$. As the wind speed approaches zero, the plume equation with dispersion coefficients expressed as functions of travel time $\bar{T} = (x/U)$ goes to zero. This is in contrast to the plume formula based on dispersion coefficients as functions of travel distance x. This function becomes infinite as $U \to 0$. In contrast to these two versions of the plume equation, concentrations estimated by the integrated puff model (Eq. 4.2) approach a $1/x^2$ distribution as $U \to 0$.

4.5 Effective Stack Height

The effective stack height H is the height above ground which best defines the centerline of the plume. The plume is assumed to originate as a point source at an altitude H feet above ground at the location of the stack. If aerodynamic downwash causes the plume to break up and mix rapidly downward in the vicinity of the stack, H may be set equal to the actual physical height H_s. Observations of a local utility indicate this phenomenon occurs frequently for wind speeds greater than 15 mph. Otherwise a plume rise ΔH is added to the physical stack height H_s, so that:

$$H = H_s + \Delta H \tag{4.7}$$

where ΔH is estimated as described below:

Smoke plume rise calculations in this model are based on a plume rise formula derived from observations at TVA stations and other power plants (Carson and Moses, 1967). (The momentum term in their original formulation is omitted in the following equation since its contribution is generally negligible compared to thermal buoyancy.)

$$\Delta H(\text{feet}) = K\, Q_s^{1/2}/U \tag{4.8}$$

where ΔH = plume rise (feet)

Q_s = heat emission rate from stack (BTU/hr)

U = wind speed (miles per hour) at the height of the stack

K = .870 (unstable - Class 3), .354 (neutral - Class 4), .222 (stable - Class 5)

Values of the heat emission rate may be approximated by a fixed percentage of the total heat rate (heating value of the fuel times the fuel rate). The percentage depends on the type and efficiency of the burning and heat exchange equipment but may be categorized as follows:

power plant - 12%

large industrial, commercial - 20%

small industrial, commercial and residential - 35%

The mean wind at the physical stack height, H_s should be used in the plume rise equation (Eq. 4.8). In evaluating the dispersion kernel (Eq. 4.3) wind at the effective stack height H, corresponding to the plume centerline, is used. In each case, the desired value for the wind speed will be usually greater than that measured at a local airport or TAM station (typically at 30 to 100 feet above the ground). Equation 4.9 provides a correction term for altitudes up to 1000 feet. The exponent p is dependent on the stability class, as shown in Table 4.3.

$$U(\text{at height } Z_2) = U(\text{at height } Z_1)(Z_2/Z_1)^P \qquad (4.9)$$

Table 4.3 Exponent for the Wind Profile Law (DeMarrais, 1959)

Stability Class	P
stable (5)	.5
neutral (4)	.2
unstable (3)	.2

The experimental data in the reference cited, indicated a slightly more uniform vertical wind speed profile for unstable than for neutral conditions, but the model is not sensitive to this distinction.

Four restrictions are placed on the use of Equation 4.8. These are listed in Table 4.4.

Table 4.4

Restrictions on the Plume Rise Formula (Eq. 4.8)

1. Mixing Layer Height (H_m):
    a. the effective stack height H, cannot be greater than the mixing layer height, H_m, if the stack is beneath the mixing layer; i.e., $H \leq H_m$ if $H_s < H_m$
    b. if the physical stack height H_s is greater than H_m an infinite value for H_m is assumed with plume rise and dispersion according to stable atmospheric conditions.
2. Low Wind Speeds (U):
    If U is estimated to be less than 4 miles per hour, the value 4 mph is used in Eq. 4.8.
3. Stability Class and the Coefficient K:
    If the physical stack height (H_s) is equal to or greater than 200 feet, K = .354 (neutral) is used even though the stability index indicates unstable conditions.

The first two restrictions (1a and 1b) in Table 4.4 are based on the assumption of an impenetrable atmospheric layer (lid) at height H_m. The effluent from a stack which emits its plume just beneath the lid will probably penetrate into the stable layer rather than obey the assumption of perfect reflection at the lid. Unfortunately, there do not appear to be any data which describe this situation.

Restriction 2 in Table 4.4 limits the minimum wind speed to be used in Equation 4.8. This reflects the fact that the equation is an empirical one in which the parameters n and m in an equation of the form $\Delta H = K\ Q_s^n\ U^m$ were found by multiple linear regression. A comparison of Equation 4.8 with TVA data (Carpenter, et al., 1967) indicates good agreement down to wind speeds of about 6 mph. Below this, the (1/u) factor in the equation causes an over-estimation of the plume rise. An arbitrary restriction on a minimum value of U in Equation 4.8 has therefore been made.

Restriction 3 occurs because for plume rise calculations the vertical variation of temperature at heights greater than 200 feet is best characterized by a neutral lapse rate even though unstable conditions may exist in the first few hundred feet above ground.

A single value of plume rise is also ascribed to each of the three classes of area sources (Sections 2.0 and 4.7) whenever the wind is less than a critical wind speed. With winds less than 6 mph, low rise residential buildings are assumed to have an effective stack height of 100 feet; high rise residential and commercial buildings, 300 feet; and industrial area sources, 300 feet. The model proves to be insensitive to these assumptions as long as the initial value of σ_z (σ_{zo}) is greater than or equal to 100 feet.

4.6 Finite Geometry

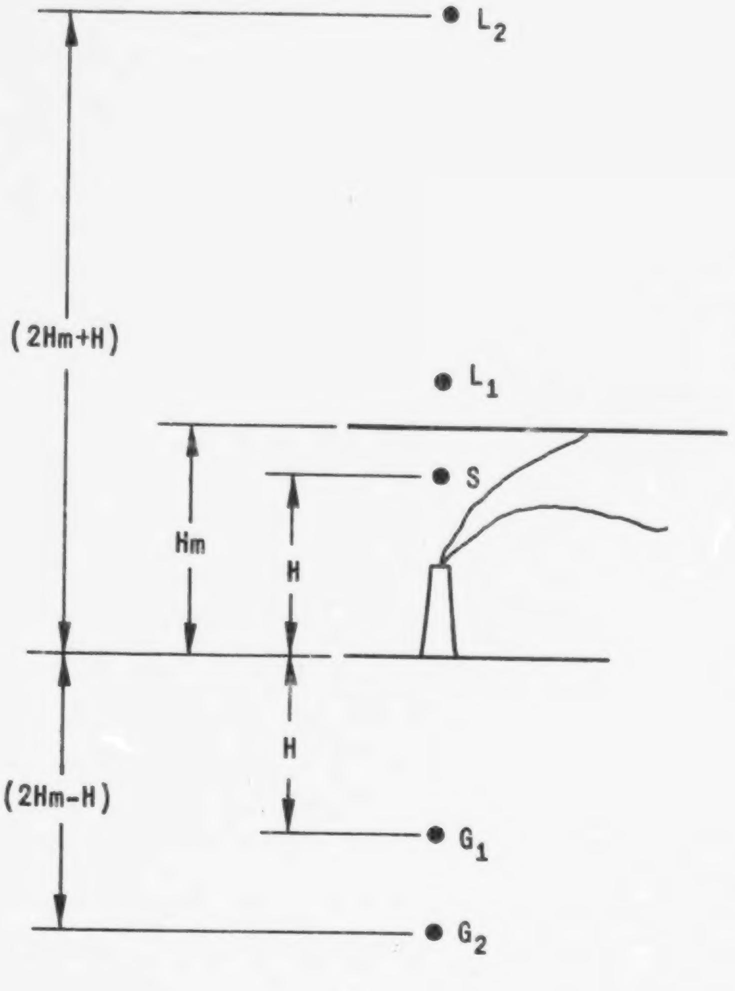
The fundamental puff kernel has been defined for z from $(-\infty, +\infty)$ with $z = 0$ on the plume axis. If we assume perfect reflection at the ground, the concentration C at time m at a receptor position (x,y,z) due to a single source at position (x',y',z') is

$$C = X(x-x',y-y',z-z',m) + X(x-x',y-y',z+z',m) \tag{4.10}$$

where the coordinates have been stated relative to the ground and Eq. 4.3 determines X.

As described in section 3 , an objective calculational procedure was developed to estimate the height of the mixing layer which is assumed to define an impenetrable barrier for vertical dispersion. In earlier work (e.g., Turner, 1967), the distribution under the lid has been calculated by a single plume until vertical diffusion implied the pollutant had reached the lid; then an abrupt transition to the equation for uniform vertical mixing would be made.

In order to avoid this abrupt transition and simultaneously to allow for time dependent (piecewise constant hourly) values of Hm, multiple reflections between ground and the inversion are represented by pairs of image sources. For example, the first image source above the lid is the reflection about Hm of the actual source; the second image source above the lid is the reflection about Hm of the first below-ground image (Fig 4.9). Depending upon the lid height and the time of travel, up to five pairs of images may be required to adequately represent a condition of uniform vertical mixing in an urban area.


L2
(2Hm+H)
L1
S
Hm
H
H
(2Hm-H)
G1
G2

113-2859-T-1

Fig. 4.9 Multiple Reflections Between a Stable Layer and Ground Represented Mathematically by Two Sets of Image Sources. The Image G_1 Is Reflected Above the Lid at L_2. The Image L_1 Is Reflected Below Ground at G_2.

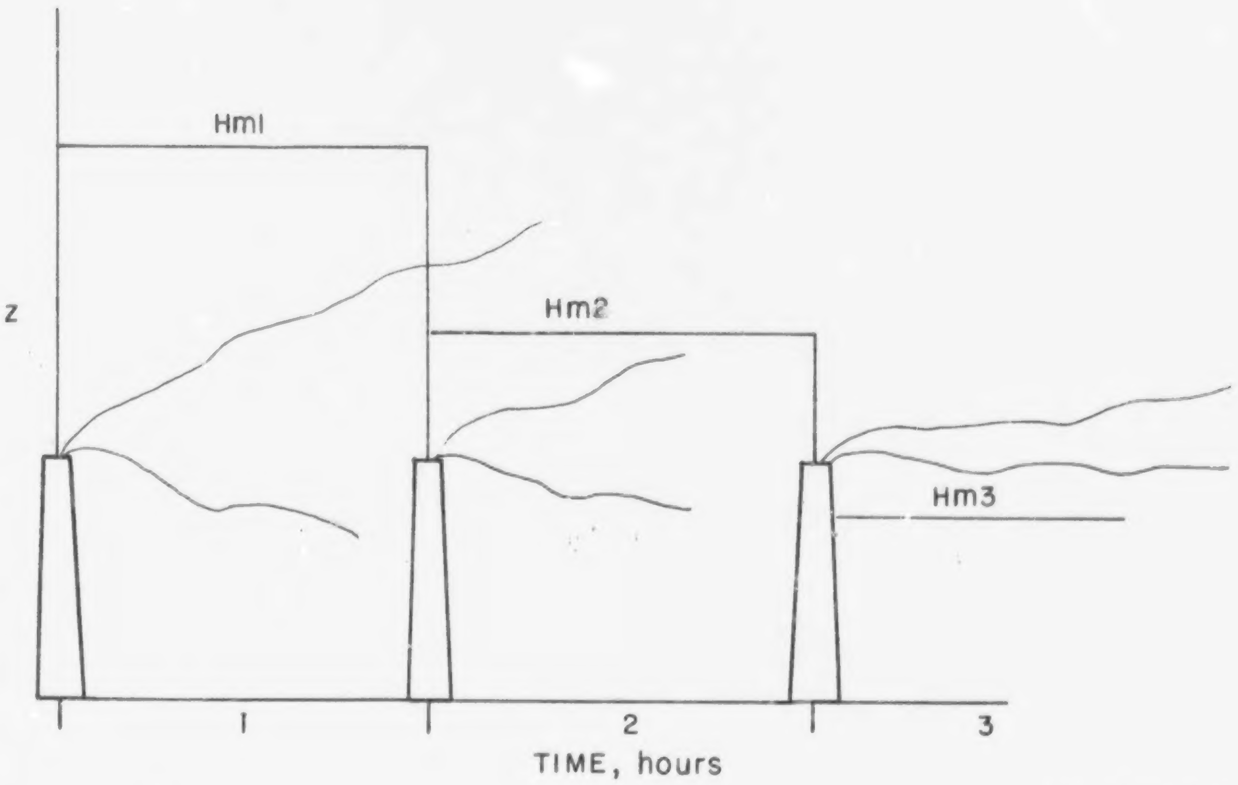
Since the lid height may vary during the lifetime of each one-hour puff, algorithms have been formulated to allow for specification of a different effective lid height for each hour m, look-back time n (see Eq. 4.2), and source J. For example, in Figure 4.10, the height of the mixing layer is steadily decreasing during the three one-hour periods. Calculations of concentrations due to stack emissions during the first hour (m=1) would be based on the lid height Hm_1 for m=1, n=1, and the lid height Hm_2 for m=2, n=1 and 2. Concentrations due to stack emissions during the second hour (m=2) would be based on lid height Hm_2 for m=2, n=1 and on Hm_3 for m=3, n=2. Concentrations due to stack emissions during the third hour (m=3) would be based on an infinite lid with diffusion coefficients corresponding to stable atmospheric conditions.

4.7 Area Sources

Earlier studies have emphasized the importance of residential coal use in determining ambient SO_2 levels. For example, at Hyde Park (TAM-4) SO_2 levels of .2 to .3 ppm for southwest winds 6 - 9 mph can be attributed almost entirely to space heating by coal fired boilers in three story buildings (Croke, 1968c).

The realistic modeling of residential zones characterized by multiple sources too numerous to represent by individual plumes is therefore critical to the success of a source oriented dispersion model for Chicago. For the Chicago grid system these so-called area sources can be visualized in one of two modes:

1) For winds less than a critical speed the individual emissions resemble plumes. For three story buildings, visual observations indicate that a representative plume rise for wind speeds less than 6 mph is about equal to the building height, i.e., approximately 50 feet.


Hml
z
Hm2
Hm3
1
2
3
TIME, hours

113-2865-T-1

Fig. 4.10 Variable Mixing Layer Height

2) Above the critical wind speed, mechanical turbulence, primarily downwash, destroys the plume slightly above the rooftop level.

Similar arguments apply to high-rise, commercial, and industrial area sources described in section 2.0. In the first case, we might approximate the area source as a uniform horizontal sheet of small thickness Δz located at $z = 100$ feet. In the second mode, it is reasonable to assume uniform mixing over the volume of the building.

The integrated puff model is ideally suited to the task of synthesizing these source configurations. In contrast to the plume equation, limited to crosswind and vertical coordinates and thereby representing a two-dimensional front, the puff incorporates the downwind coordinate and thus represents a three-dimensional cloud of pollutant.

The area source is approximated by a psuedo upwind point source. This is similar to algorithms employed in plume models, but as mentioned above, the more sophisticated puff kernel results in a volumetric source rather than a two-dimensional wave front. Therefore, in addition to a more realistic description of downwind dispersion, the puff model can evaluate directly the effect of the area source upon the area itself.

The volumetric source is synthesized by specifying three initial dispersion coefficients: σ_{xo}, σ_{yo} and σ_{zo}. These are then associated with times t_x, t_y and t_z which are the solutions to

$$\sigma_{xo} = \sigma_x(i,t_x), \ \sigma_{yo} = \sigma_y(i,t_x), \ \sigma_{zo} = \sigma_z(i,t_z) \qquad (4.11)$$

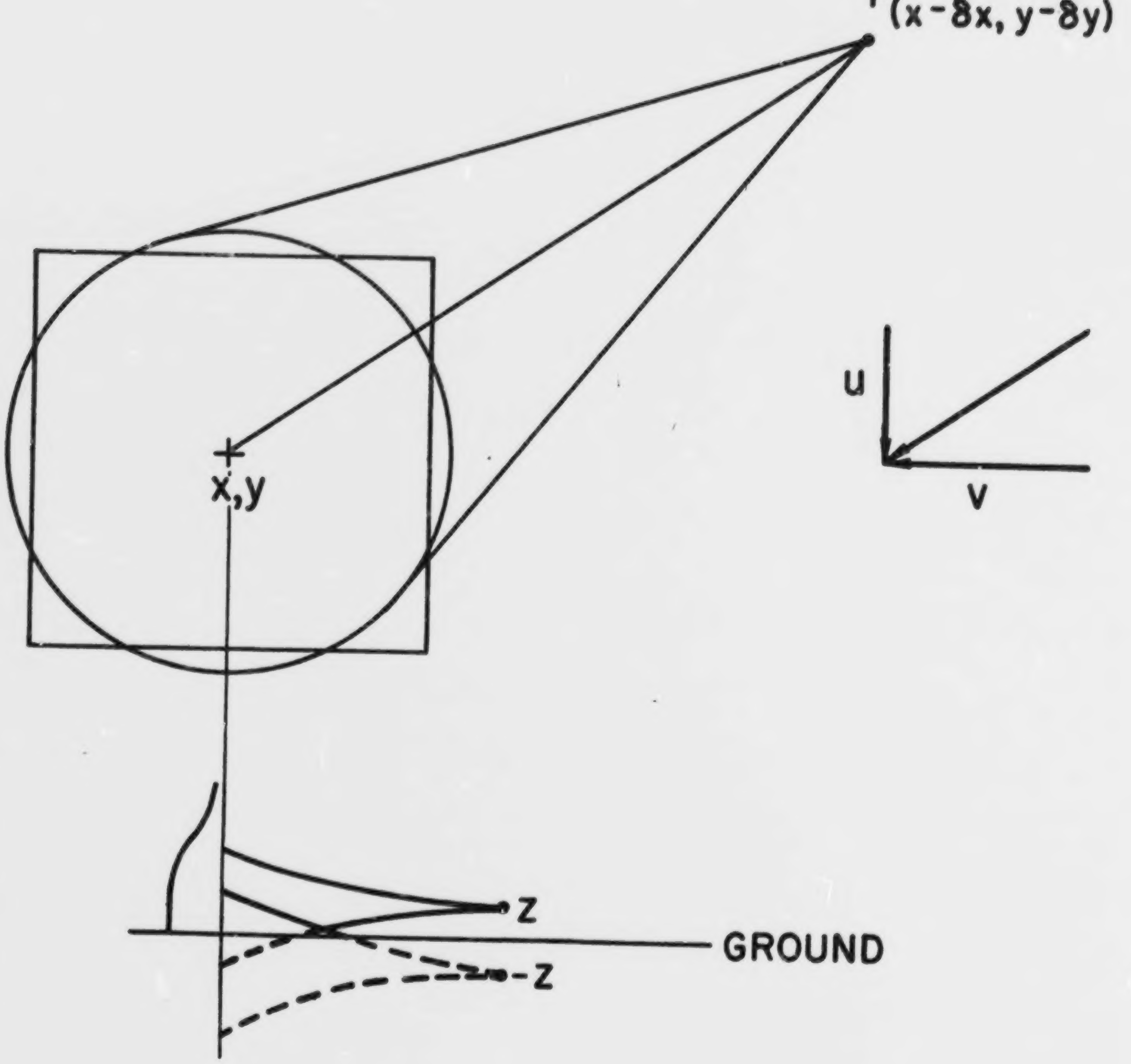
where $\sigma(i,t)$ is the family of functions describing the dispersion coefficients at time t for stability class i. A virtual source is thus defined at upwind distances $\delta_x = ut_x$ and $\delta_y = vt_y$ from the center of the area (see Fig 4.11).

The choices of σ_{xo}, σ_{yo} and σ_{zo} as well as the effective source height z depend upon the representative building height for each square mile and the mode of initial transport: plume or downwash. The transport equation (Eq. 4.3) is then modified with $x - \delta_x$ replacing x, $y - \delta_y$ replacing y, and $T + t_x$, $T + t_y$, $T + t_z$ replacing T in the appropriate locations.

For a square area source of side length n, the value σ_{yo} is defined by

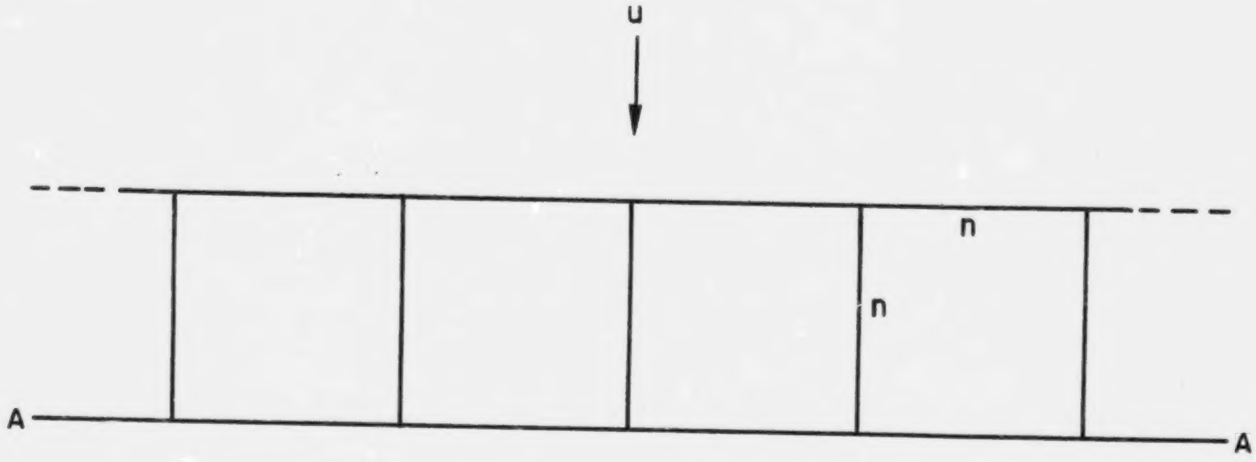
$$\sigma_{yo} = n/2.4 \tag{4.12}$$

This insures that the concentration will be independent of position along a line on the downwind side of a row of identical area sources (Fig 4.12).


P(x - δx, y - δy)
x, y
u
v
Z
GROUND
Z

113-1111

Fig. 4.11 Synthesis of an Area Source of Buildings of Height Z



113-2867

Fig. 4.12 Choice of $\sigma_{yo} = n/2.4$ Insures that Concentrations Will Be Uniform Along the Line A-A

5.0 An Integrated System for Air Resource Data Management and Dispersion Model Development

The preceding sections of this paper have described the array of emission inventory, meteorology and air quality data that was acquired and processed in order to test and validate the diffusion model. This computerized file containing nearly three years of hourly average data for a wide variety of parameters, represented a singularly valuable resource, but at the same time it presented a formidable problem in data management. The development of the "integrated puff" model required that this data file be exploited in two ways:

1) Analysis of statistically significant subsets of this array of data could be expected to yield information concerning the relative significance of many of the parameters and phenomena which were modeled. Moreover, insights into the micrometeorological characteristics of the Chicago metropolitan area might be obtained through analysis of this data. These would serve as a guide to the interpretation and evaluation of the output of the model.

2) Time series arrays of emission inventory data and raw and processed meteorology data were required as inputs to the puff model, while a corresponding array of measured sulfur oxide concentrations had to be merged and compared with its output in order to analyze and validate the theoretical predictions against real-world data. This represented a major and laborious task if manual handling of this large data file were required.

In order to achieve these objectives, an automatic data management system was clearly required. This need was met by the development of a master Air Pollution Information and Computation (APIC) system designed to automate the entire process of data storage, retrieval, manipulation, analysis, and display, which is associated with the dispersion model development effort.

The APIC system consists of the IBM PL-1 data storage and retrieval code nested in a series of operational subroutines and computational codes tailored to the analysis of air pollution data. With this system, the data stored in the master file can be partitioned in any way desired. Any combination, array or subset of emission, meteorology and/or air quality data can be formed and retrieved. The selected data array can be accessed through a FORTRAN subroutine which allows the user to manipulate the array in any desired way. For example, the analyst may form a new data array which consists of products of components of the original array raised to some power, etc. Standard subroutines for computing atmospheric stability, smoke plume rise, etc., are included as options in this system.

The array of data in the master file may be analyzed in a multivariate linear regression analysis code or a discriminant analysis code which are part of the system and the results may be displayed as tables, histograms or CALCOMP plots.

The air pollution data management system described above provides a uniquely powerful tool for the development and testing of the dispersion model. The emission simulation model described in section 2.0 and the dispersion model algorithms described in section 4.0 have been incorporated into the APICS system, so that the testing and validation process, conducted with a three-year computerized inventory of hourly average meteorology and sulfur dioxide air quality data, is totally automated. Meteorology and emission data from the master data file are input to the dispersion model, and sulfur dioxide concentrations are calculated; these results are compared with the corresponding measured air quality data and displayed in a single operation within the Argonne, IBM 360-75 computer. The sensitivity of the model to variations of critical meteorological parameters and the effects of modifications in the structure of the model itself can be tested. When the dispersion model development effort is completed in the early part of 1970, a manual of operations for the APICS system as well as for the dispersion model itself will be prepared for general use.

6.0 Results, Conclusions, and Future Studies

6.1 TAM Stations

The month of January 1967 was chosen for an initial comparison of the model with recorded sulfur dioxide data. Five TAM stations were selected. These represent a wide range of geographical and emission features (refer to Fig 2.1).

TAM 1, situated in a low density residential area in the northwest corner of the city, sees little SO_2 unless southeasterly winds carry plumes from the powerplants and other industries 11 miles away.

Prevailing southwest winds are responsible for high concentrations occasionally observed at TAM 2. This station is also influenced by the high-rise concentration along the lakeshore during northeasterly winds, especially during lake breeze conditions.

TAM 3 generally records the highest sulfur dioxide levels in the city. It is situated in the midst of coal burning commercial buildings (for example, Union Station, several blocks to the west emitted 8×10^6 pounds of SO_2 per year until it recently shifted to gas). Furthermore, southwest winds, sweeping up the "industrial corridor" along which are located three power plants and major industries, cause extremely high pollution concentrations downtown, especially when vertical ventilation is limited by an inversion. Peak hourly averages greater than 1 ppm have been recorded.

TAM 4 is situated along the lake at the edge of over 20 square miles of coal burning three story residences. Studies of the frequency of air pollution incidents in Chicago from January 1966 - December 1967 indicate that this station has the highest number of midwinter short term air pollution incidents (6 hrs - 24 hrs duration). For example, in January 1966 and January 1967, TAM 4 had a total of 30 six-hour periods for which SO_2 levels exceeded .4 ppm. The corresponding figures for TAMS 1, 2, and 3 are 0, 1, and 8. Furthermore, plumes from the industrial corridor seven miles northwest are often sensed at TAM 4.

TAM 5 is similar to TAM 1 except that northerly winds are responsible for occasionally high SO_2 levels. Other TAM stations (6 - 8) were not included in this initial validation effort because they are situated on the borders of the city, and no inventory has yet been assembled for the areas of Cook County immediately outside the city limits or for the Gary-Hammond, Indiana, industrial zone.

Ninety-seven station-days (2328 hourly values) were studied for the month of January 1967 at TAM stations 1 - 5. A station malfunction on any particular day eliminated that station from the data set for that day. Malfunctions, either due to sensor or transmission difficulties, are automatically logged on the original Chicago air quality tapes.

6.2 Computer Requirements

The model has been programmed for the IBM-360 computer. Since each hourly time step for each source and each receptor involves a numerical integration, some effort has been expended to:

1) limit the number of integrations by employing a preliminary test to estimate whether or not a particular plume is likely to contribute to a given dose point (for example, there is no reason to evaluate the contribution from a stack located 5 miles downwind of the receptor);

2) approximate integrals, where possible, by the mean value theorem

3) lump distant area sources together.

As presently constructed, the model run with hourly time steps requires between .5 and .75 minutes of computer time per station-day. Thus the run for five TAM stations for the 97-station-days in the month of January 1967 required less than two hours. Recent analytical work (see section 4.4) indicates that dispersion coefficients can be approximated by the linear relationships $\sigma_y = \alpha T$, $\sigma_z = \gamma T$. Under these circumstances, the integral (Eq. 4.3) can be evaluated in closed form. It is anticipated that run time with this modification will be approximately equal to that required for a standard plume model.

6.3 Statistical Results

There are numerous statistical tests which have been applied to source oriented pollution dispersion models. The importance attached to any particular test clearly depends upon the use to which the model is to be put (Moses, 1969). One of the more standard presentations involves evaluating the percentage of calculated values within a given tolerance of the corresponding observed values. This is equivalent to a scattergram, less dazzling and more easily interpreted.

Table 6.1 lists these percentages for each TAM station and for the citywide collection. Hourly data and 2-hour, 6-hour, and 24-hour averages are evaluated in terms of four criteria.

Monthly and daily predictions are in excellent agreement with observed values. Marsh and Withers (1969) indicate that, for their Reading, England, model

TABLE 6.1

ITEM	-Hour Avg.	TAM STATIONS					
		1	2	3	4	5	1-5
Mean ($^{\mu}$obs)	-	.06 ppm	.12 ppm	.33 ppm	.15 ppm	.06 ppm	.14 ppm
$\frac{(\mu obs - \mu calc)}{\mu obs} \times 100\%$	-	- 10%	+ 16%	+ 14%	- 3%	- 9%	+ 7.4%
Std.Dev.(obs-calc)	1	.09 ppm	.10 ppm	.20 ppm	.13 ppm	.10 ppm	.13 ppm
Std.Dev/Mean	1	1.7	.88	.62	.84	1.6	.93
% ± .025 ppm	1	58%	37%	12%	26%	45%	35%
% ± .05 ppm	1	69%	63%	23%	53%	71%	57%
% ± .1 ppm	1	84%	81%	47%	79%	89%	77%
#Data Points	-	288	576	432	408	624	2328
Std.Dev.(obs-calc)	2	.08	.09	.18	.11	.09	.12
Std.Dev/Mean	2	1.3	.78	.56	.77	1.5	.83
% ± .025 ppm	2	58%	40%	15%	29%	45%	37%
% ± .05 ppm	2	70%	66%	27%	52%	70%	58%
% ± .1 ppm	2	83%	83%	49%	81%	88%	78%
#Data Points	-	144	288	216	204	312	1164

Contd.

TABLE 6.1 (Contd.)

Statistical Analysis of Dispersion Model Results - January 1967

ITEM	-Hour Avg.	TAM STATIONS					
		1	2	3	4	5	1-5
Mean ($^{\mu}$obs)	-	.06 ppm	.12 ppm	.33 ppm	.15 ppm	.06 ppm	.14 ppm
Std.Dev(obs-calc)	6	.07	.08	.14	.09	.07	.09
Std.Dev/Mean	6	1.1	.65	.42	.58	1.2	.64
% ± .025 ppm	6	56%	36%	10%	32%	46%	36%
% ± .05 ppm	6	67%	66%	29%	54%	72%	59%
% ± .1 ppm	6	90%	88%	56%	85%	91%	83%
#Data Points	-	48	96	72	68	104	388
Std.Dev(obs-calc)	24	.04 ppm	.05 ppm	.10 ppm	.07 ppm	.04 ppm	.06 ppm
Std.Dev/Mean	24	.71	.44	.30	.45	.70	.43
% ± .025 ppm	24	25%	46%	17%	59%	58%	43%
% ± .05 ppm	24	75%	62%	39%	77%	77%	66%
% ± .1 ppm	24	100%	96%	67%	88%	96%	90%
#Data Points	-	12	24	18	17	26	97

as well as for others in the literature, the ratios of the standard deviations (observed - calculated) to the observed means are all higher than 1.1. From Table 6.1, the corresponding value for 24-hour averages is .43. It is .64 for 6-hour averages and .93 for one-hour averages.

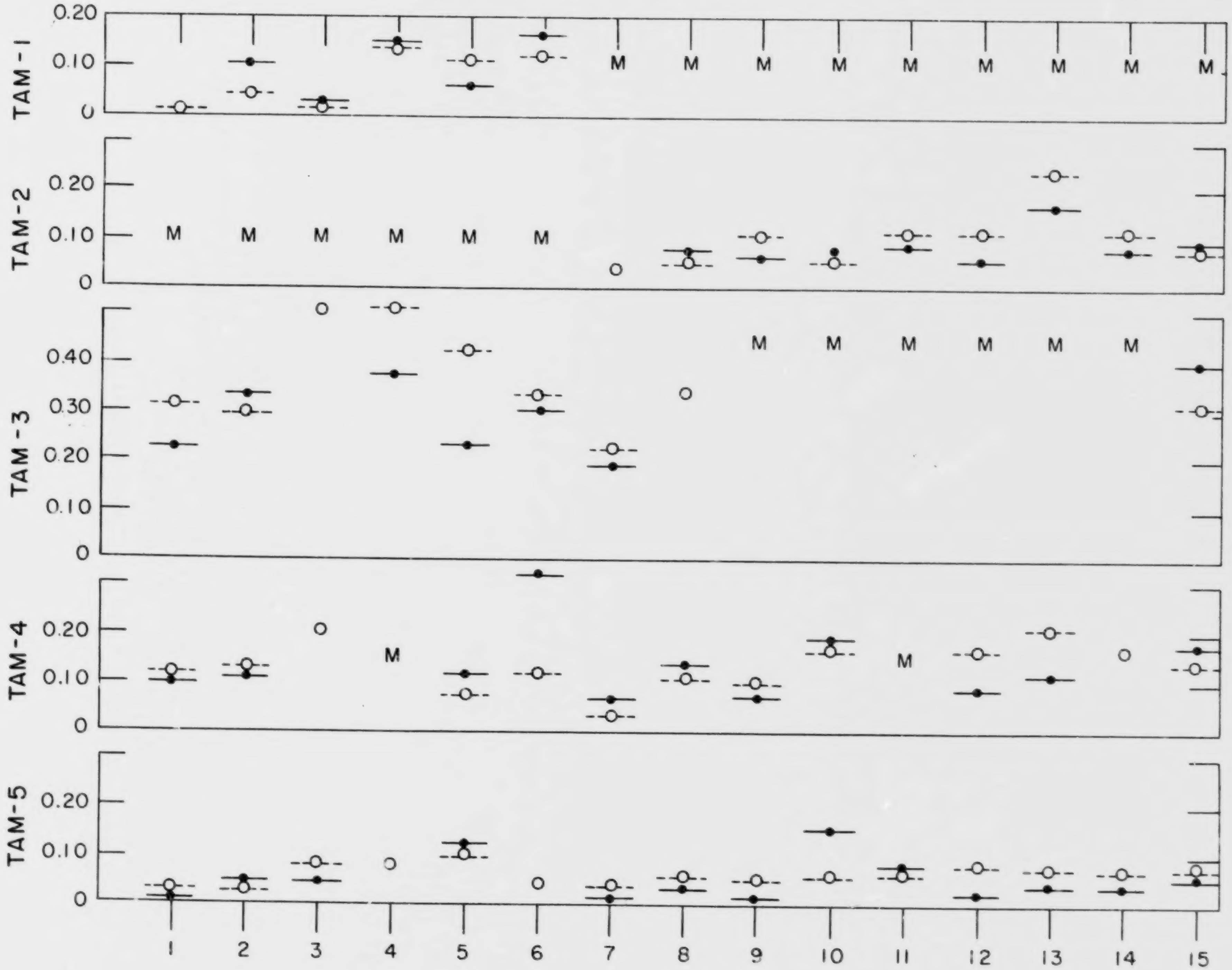
Results for individual TAM stations vary depending primarily upon the monthly mean. For example, almost all values for TAMS 1 and 5 fall within ± .1 ppm since the means are only .06. However, for the same reason the ratios $(\sigma_{obs-calc})/\mu_{obs}$ are high for these stations.

Figure 6.1 shows daily averages at TAMS 1-5 for January 1967. Six-hour averages are presented in Table 6.1 because this is the minimum practical time step for the implementation of incident control strategies (Croke and Booras, 1969). On a citywide basis 59% of the calculated 6-hour values are within ± .05 ppm and 83% within ± .1 ppm.

The results for 6-hour averages are also presented in Table 6.2 Assuming the solid lines delineate a region of successful predictions, then 59% of the calculations are "correct." The skill score (based on chance) is .42; the model explains 52% of the variance in the observed data set. For 24-hour averages, this statistic is 74%.

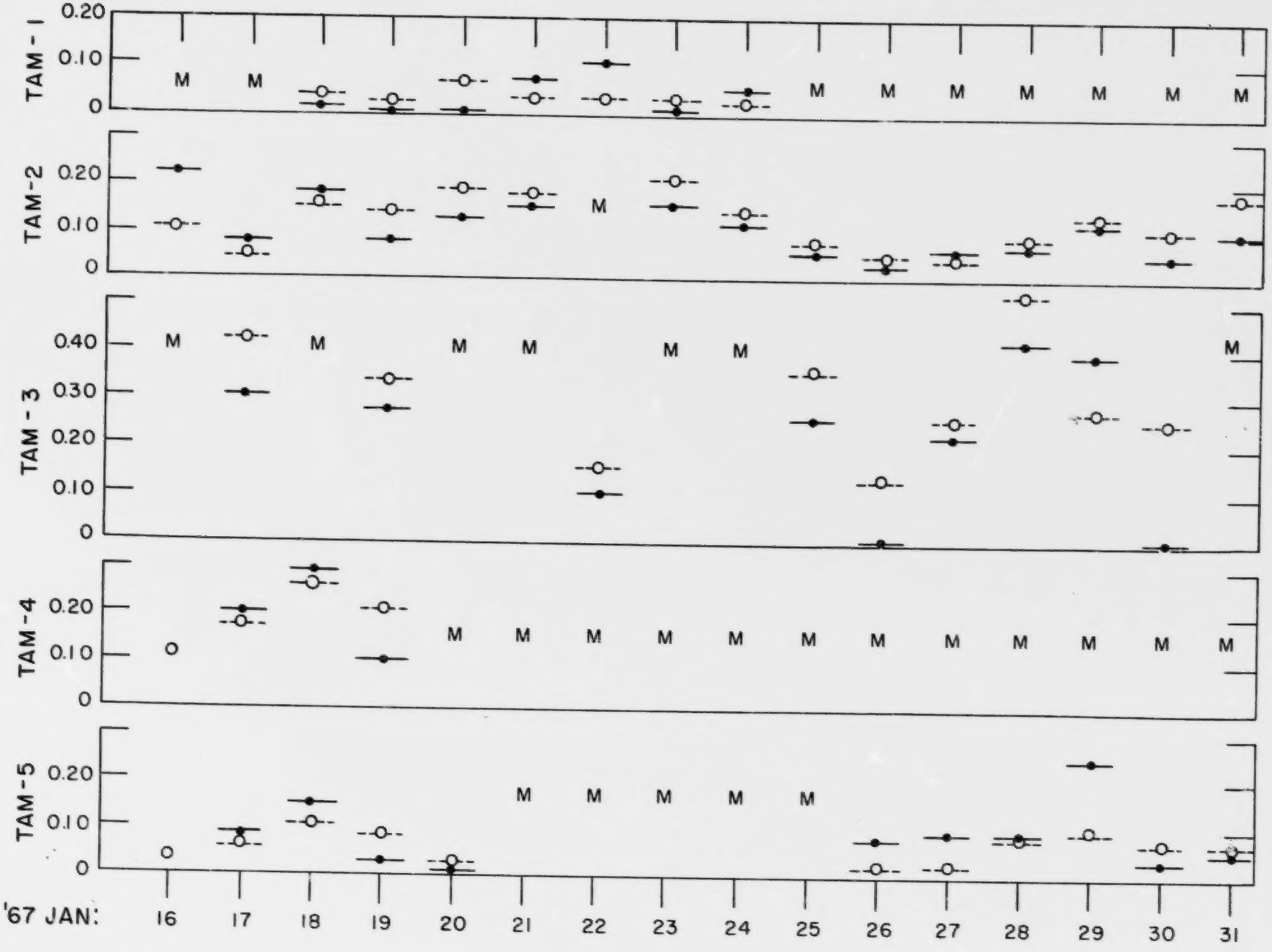
Tables 6.3 and 6.4 illustrate the use of the model in evaluating the frequency of short term air pollution incidents. The contingency tables are based on the following air pollution "war game" rules:

1) A threshold SO_2 level is defined for a given averaging period.
2) If the model predicts that this level will be exceeded, then action is taken.
3) If action is taken and the observed average is greater than the threshold less a tolerance (here .025 ppm), then an incident is said to have actually occurred.
4) If no action is taken and the observed average is less than the threshold plus a slight tolerance (here .025 ppm), then an incident is said not to have occurred.



113-2879

Fig. 6.1a Daily Averages - January 1967.

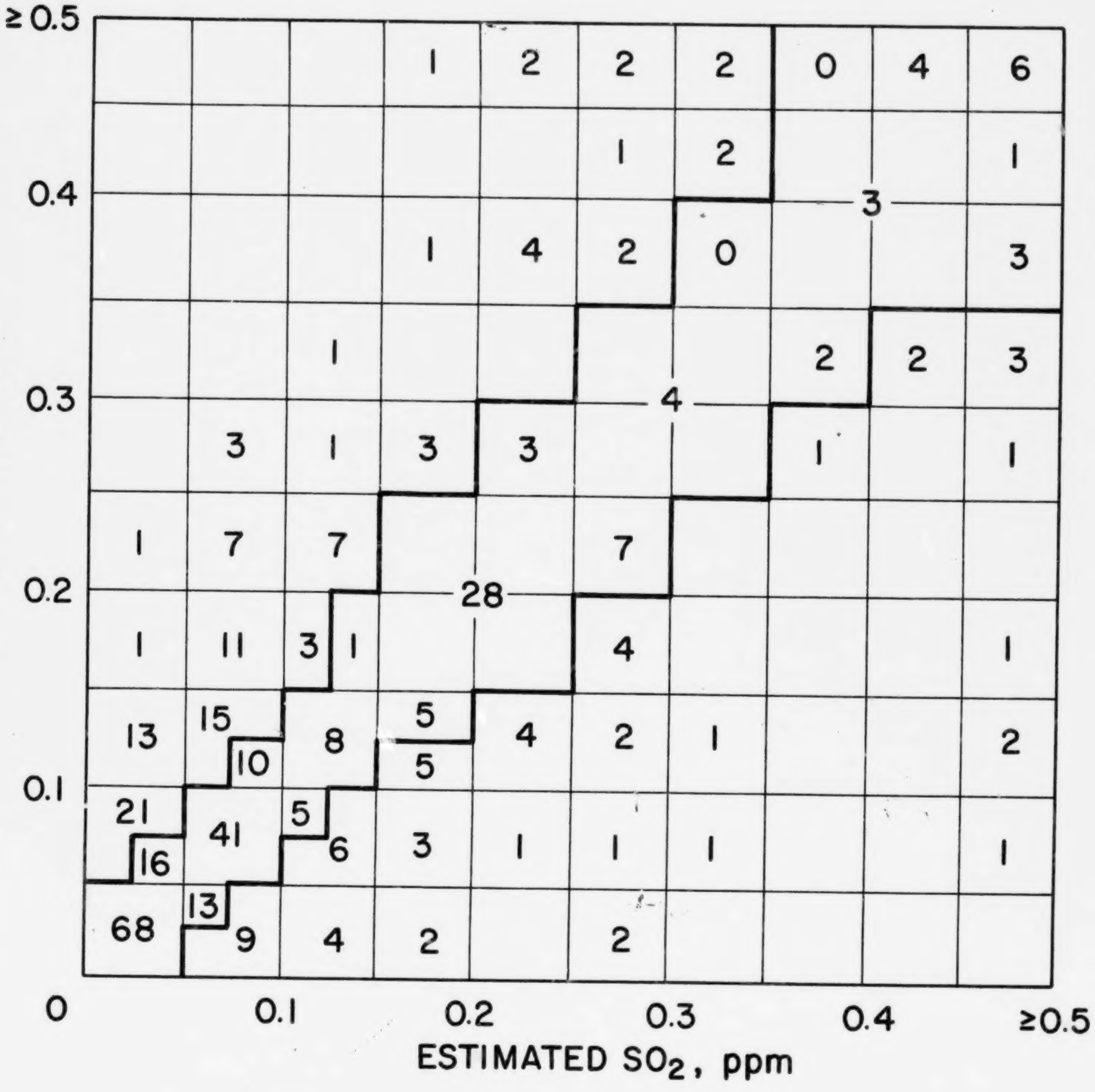


113-2868

Fig. 6.1b Daily Averages - January 1967.

TABLE 6.2
TAM Stations 1-5, 6-hr SO_2 Averages - 1967

113-2866



≥0.5
0.4
0.3
0.2
0.1
OBSERVED SO_2, ppm
0
0.1
0.2
0.3
0.4
≥0.5
ESTIMATED SO_2, ppm

			1	2	2	2	0	4	6
					1	2			1
			1	4	2	0	3		3
		1					2	2	3
	3	1	3	3	4		1		1
1	7	7		28	7				
1	11	3 1			4				1
13	15 10	8	5 5	4	2	1			2
21 16	41	5 6	3	1	1	1			1
68	13 9	4	2		2				

TABLE 6.3

TAM Stations 1-5
24-Hr Incidents - January 1967

Symbol	Threshold	Tolerance	Skill Score (Based on Chance)
x	.1 ppm	.025	.76
y	.2 ppm	.025	.73
z	.3 ppm	.025	.75

		Predict	
		Yes	No
Occur	Yes	x 44	x 9
		y 17	y 6
		z 9	z 1
	No	x 3	x 41
		y 3	y 71
		z 3	z 84

TABLE 6.4

Stations 1-5
6-Hr Incidents - January 1967

Symbol	Threshold	Tolerance	Skill Score (Based on Chance
x	.1 ppm	.025	.76
y	.2 ppm	.025	.64
z	.3 ppm	.025	.80

		Predict	
		Yes	No
Occur	Yes	x 145	x 32
		y 62	y 28
		z 32	z 10
	No	x 14	x 197
		y 20	y 278
		z 6	z 340

When compared to chance, the model is significant at better than the 99.9% confidence level and the skill scores for this air pollution war game range from .64 to .80. Skill scores are defined by the ratio $(V-V^1)/(T-V^1)$ where V is the number of correst estimates (here yes*yes + no*no cases), T the total number of cases, and V^1 the value of V expected by some means other than the model under evaluation. For example, instead of chance, a simpler plume model might be used. It is worth noting also that in terms of incident control policies, taking serious actions such as temporarily curtailing industrial production is costly. Air pollution cost-benefit studies conducted at Argonne show that as much as $10 million per day can be involved in lost wages and production for a city such Chicago. Thus, in practice, the tolerance used above would be enlarged sufficiently to insure that the model scores significantly better than shown in Tables 6.3 and 6.4.

6.4 Hourly Time Series

Figure 6.2 is a collection of stripcharts for January 1967 showing hourly wind speed, wind direction, temperature (all measured at Midway Airport), atmospheric stability class, and the mixing height as estimated by the objective method described in section 3. Figure 6.3 is a collection of strip charts also for January 1967 showing smoothed hourly values of observed (solid lines) and estimated (dotted lines) sulfur dioxide for TAMS 1-5. For readability, the hourly values have been smoothed by the formula: $X(n) = 1/4(X(n-1) + 2X(n) + X(n+1))$, where n is the hour number. They are then approximately equivalent to two-hour averages. Missing data is denoted by an 'M'.

This would appear to be the first paper which presents time series such as these. They clearly show that the model, which statistically looks very promising, has its exceptionally good and equally disappointing moments. The model as presently constructed has a number of strong points: among them, a dispersion kernel which can respond in a physically realistic way to transients in wind direction, wind speed, source strength, and mixing layer height, and which synthesizes area sources exceptionally well; an industrial inventory which estimates seasonal and daily shift patterns based on an emission inventory procedure geared to a boiler room superintendent; an objective mixing layer height estimation technique which, although suffering from the obvious problems of extrapolating vertical temperature profiles over distances greater than 100 miles, correlates well with subjective estimates of diurnal trends; and an overall system of data storage, retrieval, and analysis designed to meet the operational requirements of an urban air pollution control administration. Weak points are also evident: most significantly, a poor determination of the wind field which should be improved by deriving an hourly wind map but which, in any event, is limited in Chicago by the accuracy of the TAM aerovanes. The model under certain circumstances is also extremely sensitive to meteorological parameters - both observed and derived. For example, when the height of the mixing layer approaches the physical stack height of a major power plant, the calculation of ground level concentrations due to that plant may vary by a factor of 10 or more, depending upon whether the plume is assumed to travel above or be trapped beneath the lid. There are also further refinements which should be made in the model: For example, major point sources and area sources outside the city limits must be included in the emission inventory; the local effect of the topography of city center on the mixing layer height and the effective atmospheric stability should be included; plume rise formulations might be modified to synthesize a gradually ascending plume; the run time can be greatly reduced if the equations can be analytically integrated.

The strip charts give clear evidence of many of these items. The results, magnitudes, and trends appear to be sufficiently consistent to test selected hypotheses, about both the model and the air pollution meteorology of the urban area. The following is a list of topics for which the hourly time series of meteorological and air quality variables give evidence.

The Importance of Residential and Commercial Heating Sources and Low Lying Industrial Sources

This can be seen easily by an overall comparison of ambient SO_2 levels at the five stations with emission maps in Section 2. The model predicts station means for January to better than ± 20%.

The Importance of Wind Direction

January 9 and 10 at TAM 4 are days of almost constant temperature (28°F), wind speed (15 mph), and mixing layer height (2000 ft). Yet the SO_2 level rises steadily from below .1 ppm on January 9 to .2 ppm on the 10th as the wind swings from 220° (comparatively low residential emissions) to 270° (significantly higher residential emissions) to 300° (high residential emissions plus the distant industrial area). On the same two days, TAM 2 sees approximately the reverse trend of upwind source concentrations. TAM 3, on January 27, responds to a gradual shift in wind direction from NE to NW.

Large Point Sources are Assumed to Touch Ground - But Do Not

The Crawford power plant (III in Fig 2.1), as opposed to others with different stack configurations, is regularly predicted to reach ground level whenever its plume centerline passes over TAM 5 (4 miles south), but consistently, it is barely detected - for example, TAM 5, Jan. 5, 10, 27, 29.

Large Point Sources Trapped Beneath a Lid Cause Very High Concentrations Downwind.

For example: TAM 1, Jan 1, 4, 5
TAM 3, Jan 15 (note dropping lid had little influence on TAM 2)
TAM 2, Jan 21, 23

Periods of Very Low Winds ($\leq$ 5 mph) occur on the following occasions:

Jan 3 (0300-0800) - 5 (1300-1600) - 13 (0600-0900) - 18 (1000-1300)
21 (2000-2200) - 23 (1800-2400) - 24 (0000-0900) - 25 (1800-2400).

Almost uniformly, the model yields satisfactory predictions of trends and magnitudes of SO_2 levels during these critical periods of low winds and potentially high SO_2 levels.

Transition Hours - Sunrise and Sunset

From 0600-1000 and from 1500-1900 are diurnal periods of significant change in the dispersive capacity of the urban atmosphere. The model is influenced during these periods by changes in atmospheric stability and mixing layer height. The model appears capable of simulating the corresponding diurnal trends in SO_2 level, although occasionally the sensitivity of the relationship between assumed lid height and physical stack height of upwind point sources, causes large discrepancies between predicted and observed concentrations (ex. TAM 4, Jan 6).

The Emission Inventory should be extended beyond the city limits. For example, TAM 5 is consistently under-predicted when winds are from the SW. The receptor is 4 miles from the Cicero residential/commercial area. Approximately 20 miles to the southwest is the Romeoville Power Plant which regularly emits more than 2×10^6 lb SO_2 per hour. For a southwest wind at 10 mph, the plume concentration on the ground at TAM 5 is approximately .03 ppm with no lid present. Examples of underpredictions at TAM 5 during SW winds:

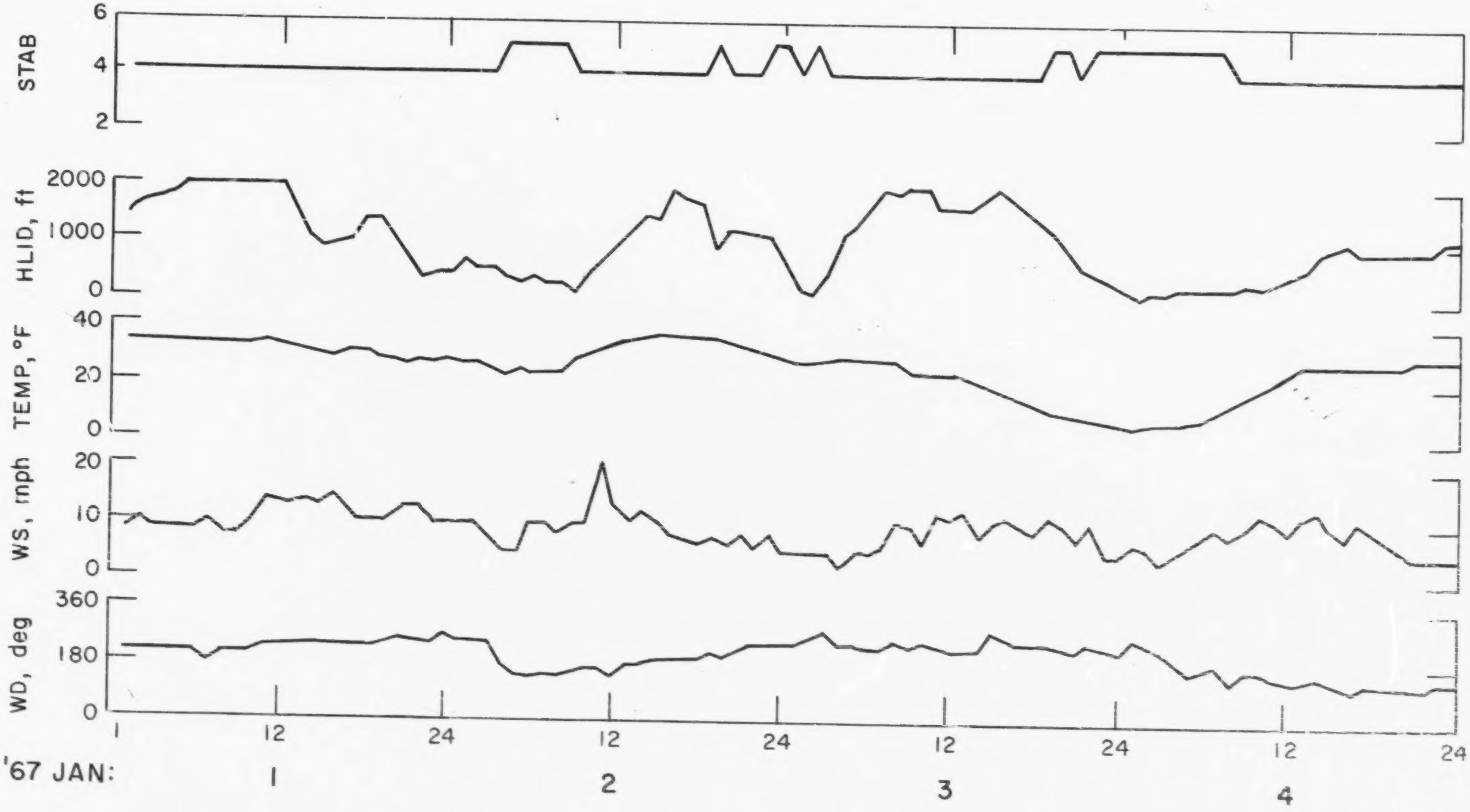
Jan 9, 11 (midday) - 12 (midday) - 13 (midday) - 19.

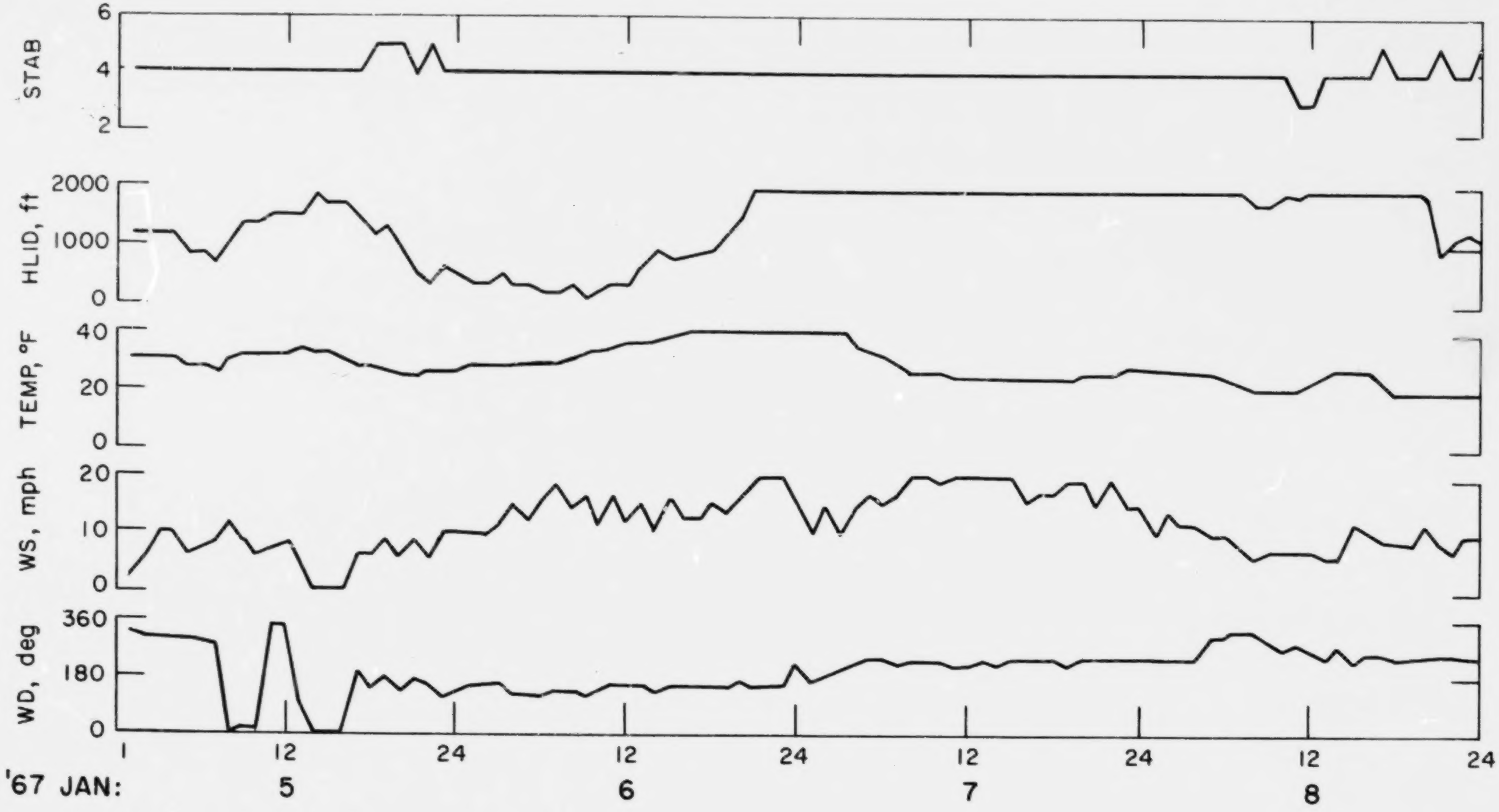
Abrupt Changes in Windspeed and Direction Occur on

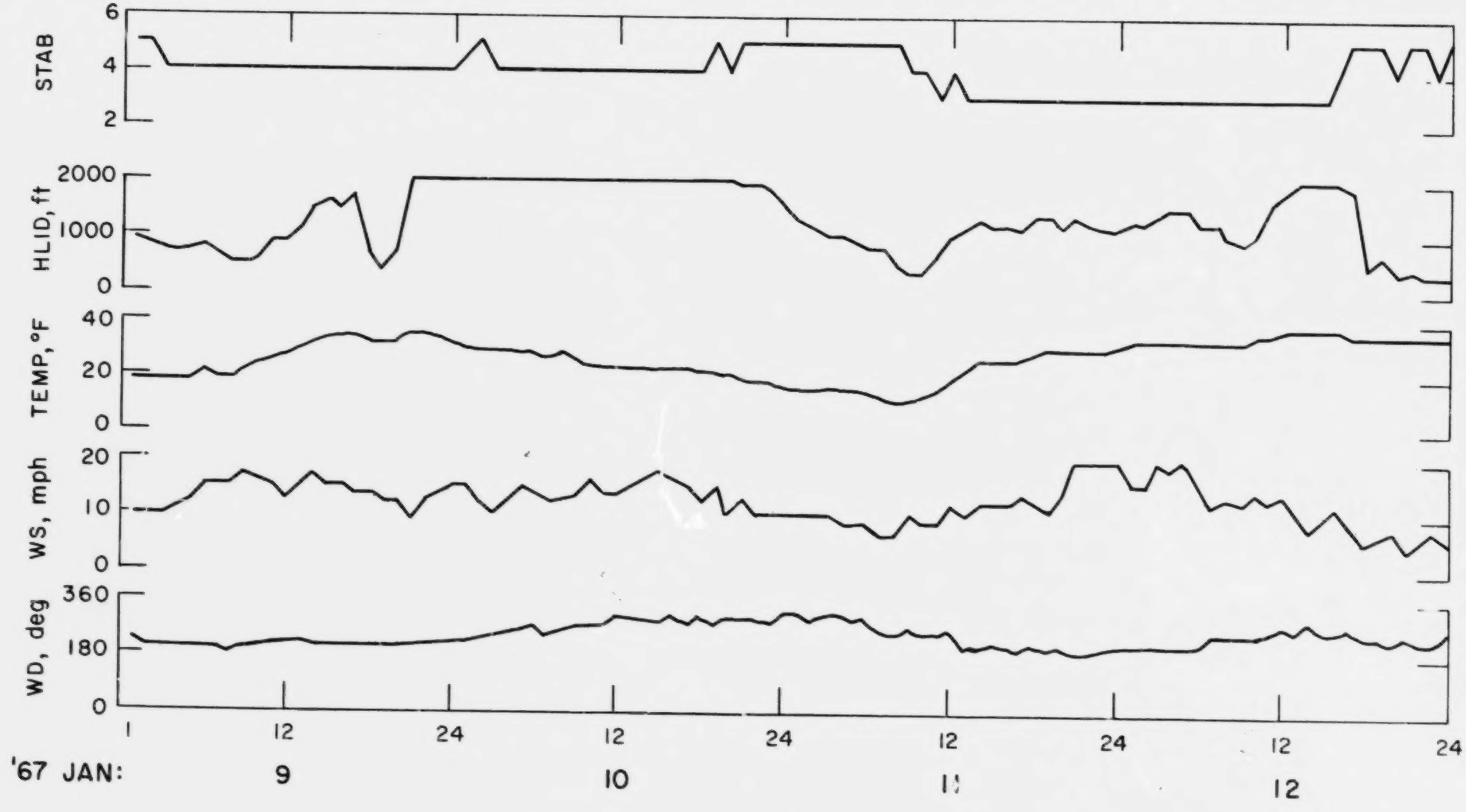
Jan 23 (1800) - Jan 24 (0700) - Jan 28 (2300) - Jan 29 (1300).

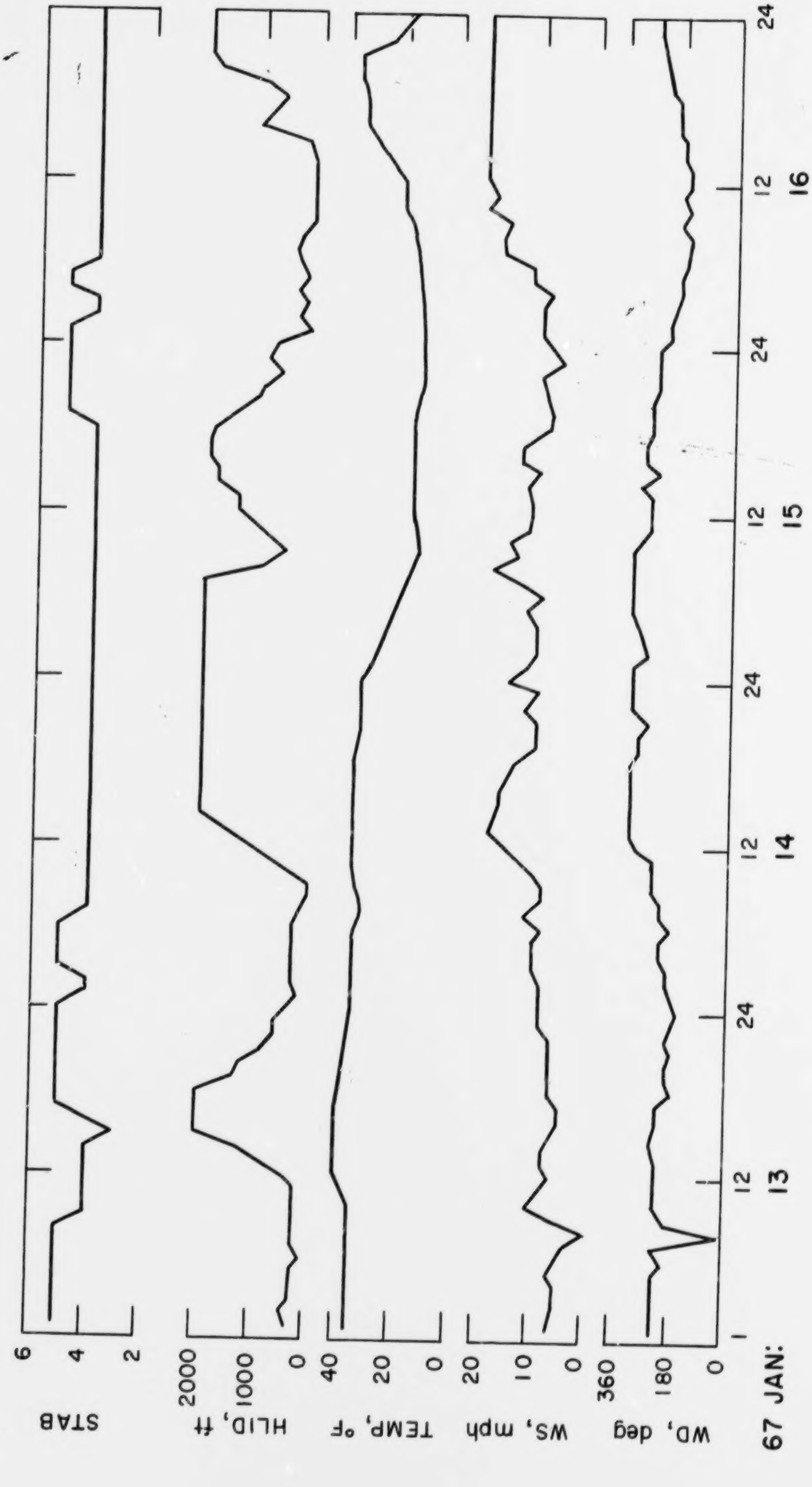
These are simulated with acceptable accuracy.

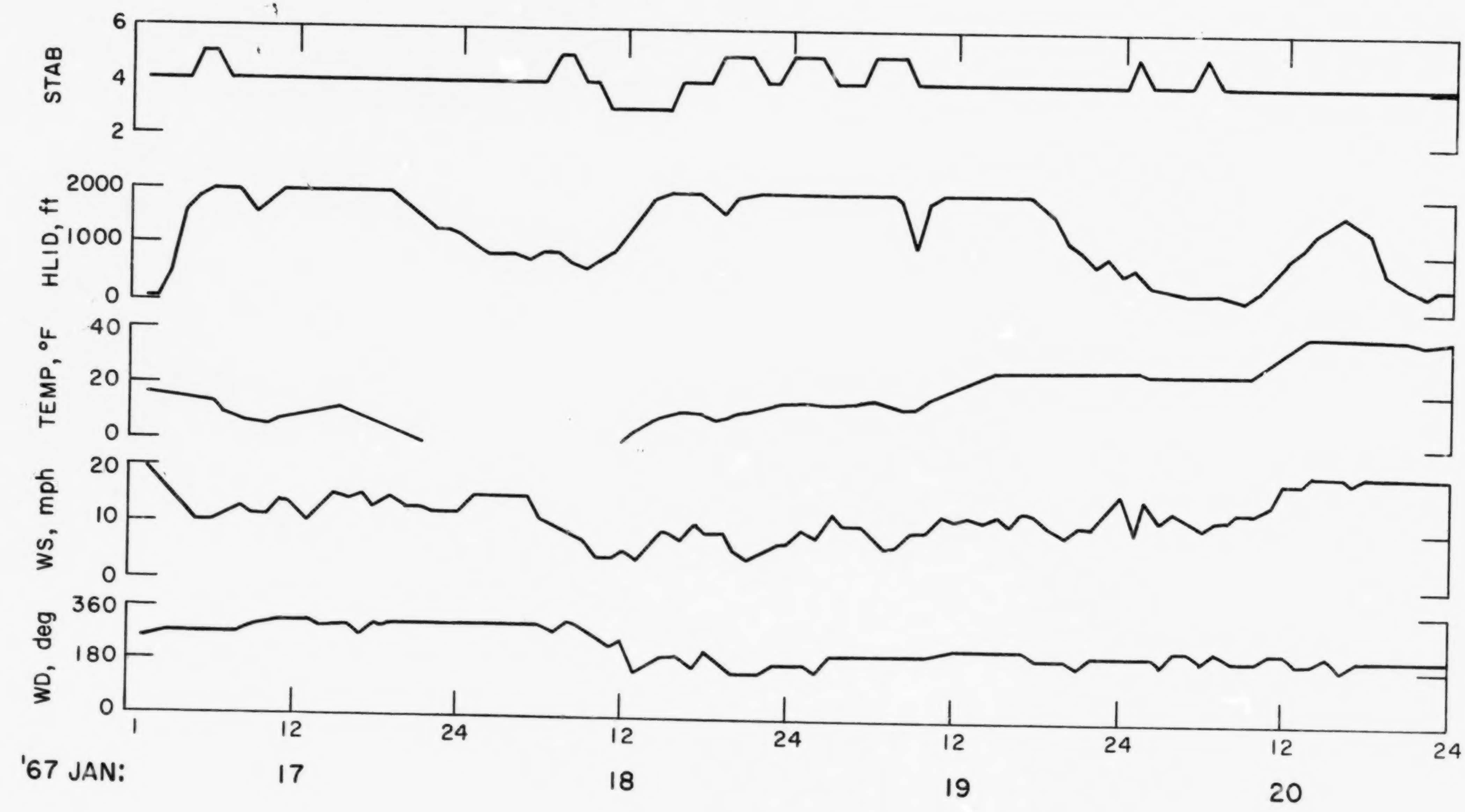
Fig. 6.2 Hourly Values of Wind Speed and Direction, Temperature (from Midway Airport), Atmospheric Stability Classification, and Estimated Height of the Mixing Layer. January 1967

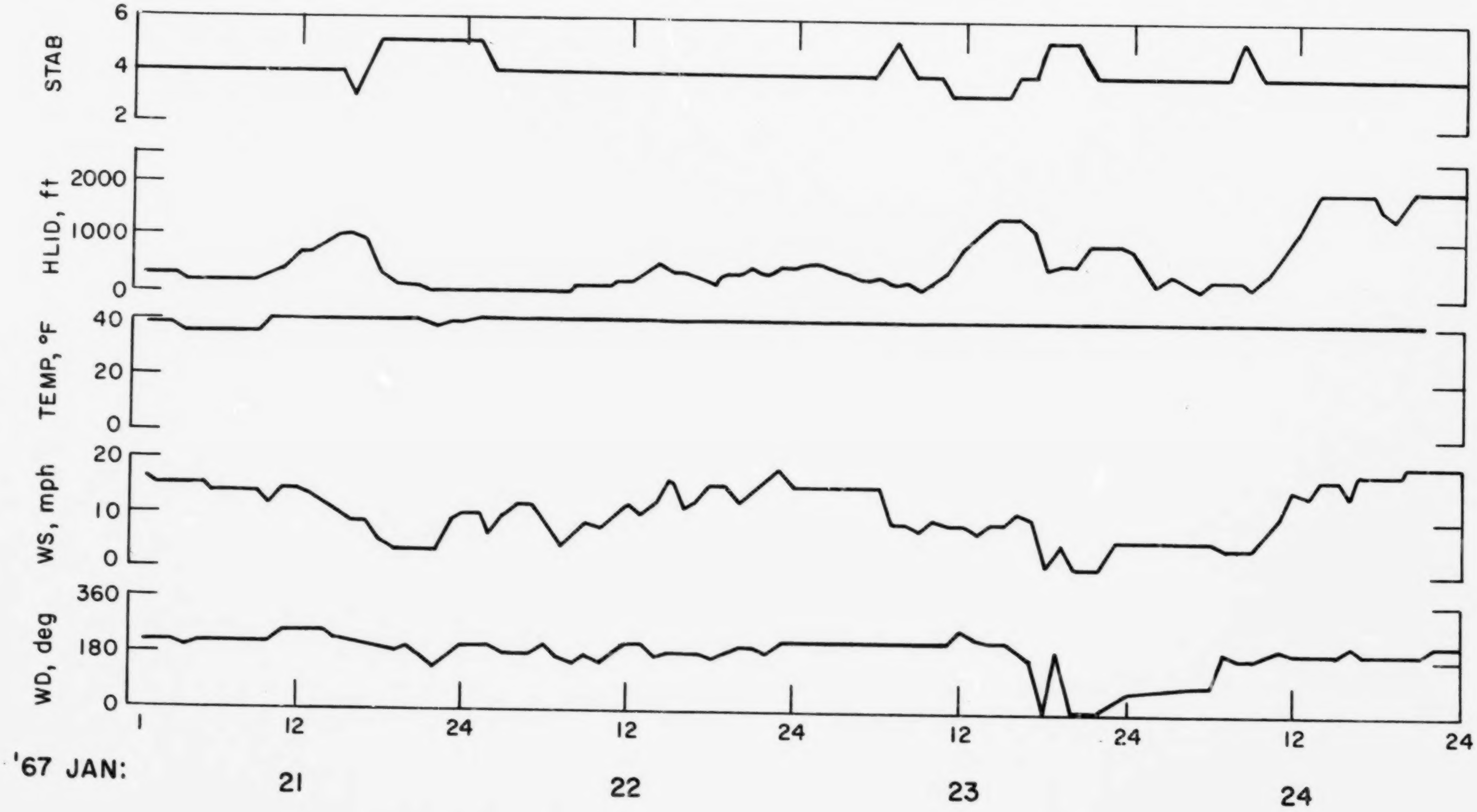

STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
0
1
12
24
12
24
12
24
12
24
'67 JAN:
1
2
3
4

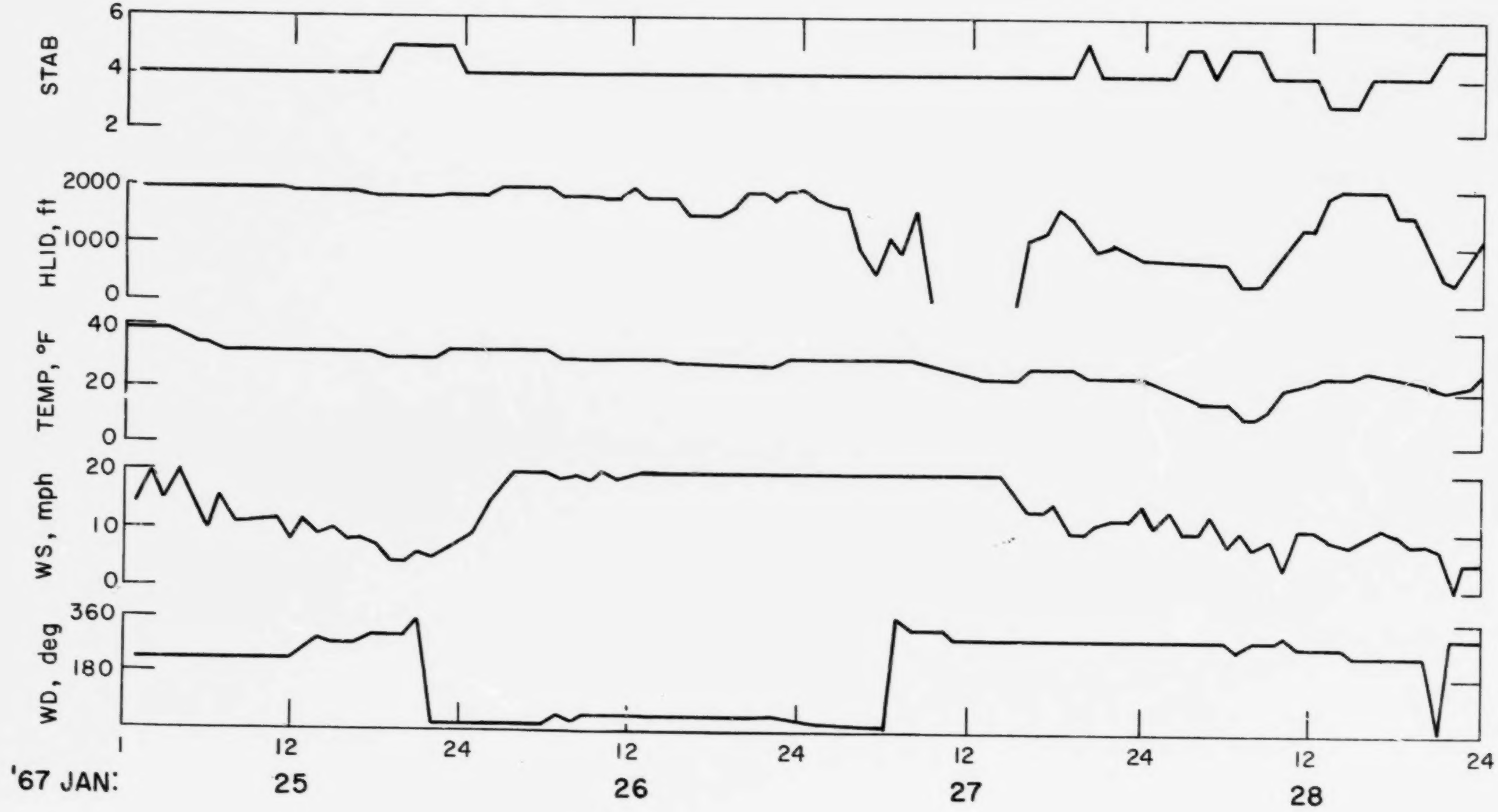

STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
0
1
12
24
12
24
12
24
12
24
'67 JAN:
5
6
7
8


STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
0
1
12
24
12
24
12
24
12
24
'67 JAN:
9
10
11
12


STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
0
67 JAN:
1
12
13
24
12
14
24
12
15
24
12
16
24


STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
0
1
12
24
12
24
12
24
12
24
'67 JAN:
17
18
19
20


STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
0
1
12
24
12
24
12
24
12
24
'67 JAN:
21
22
23
24


STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
1
12
24
12
24
12
24
12
24
'67 JAN:
25
26
27
28

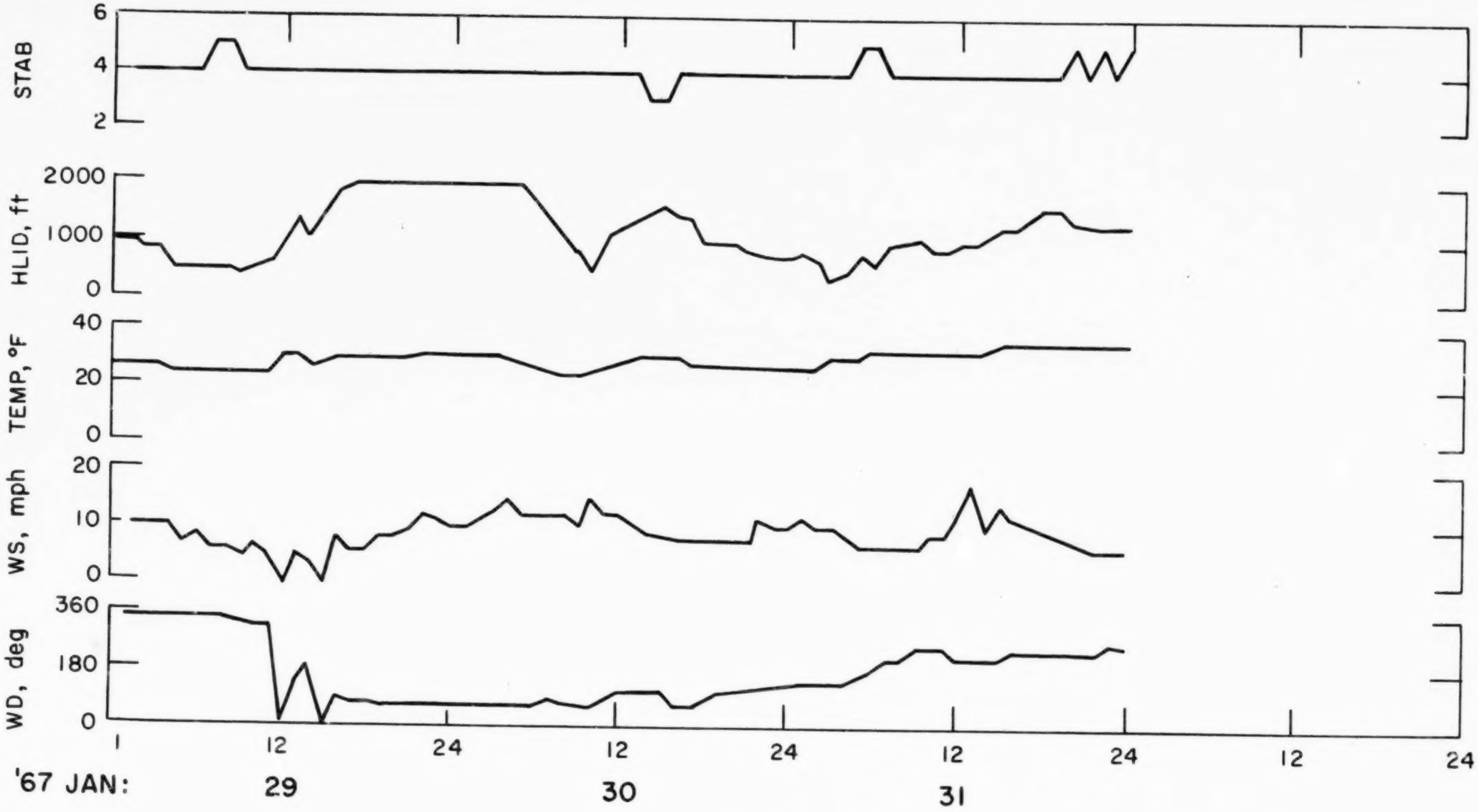
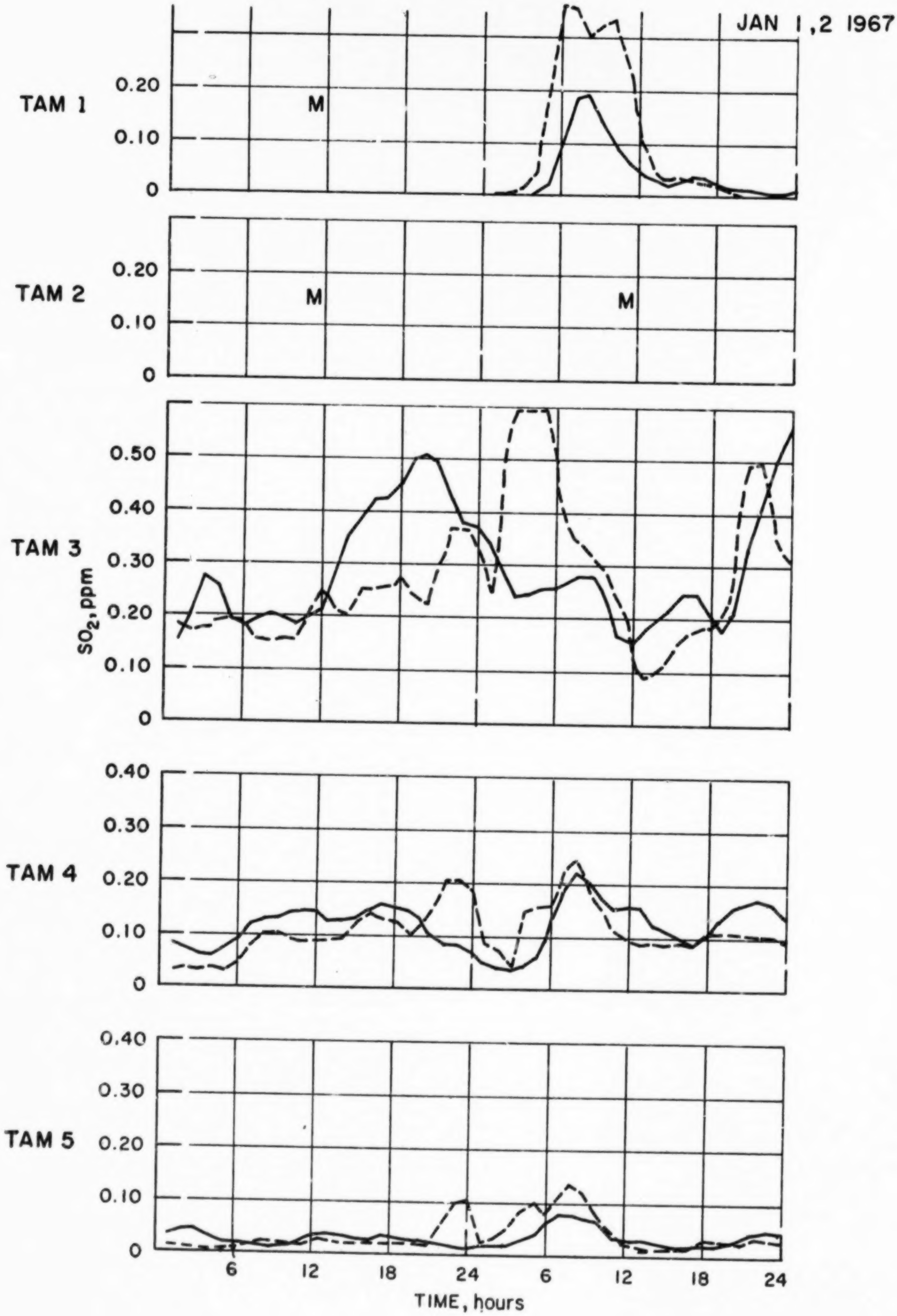
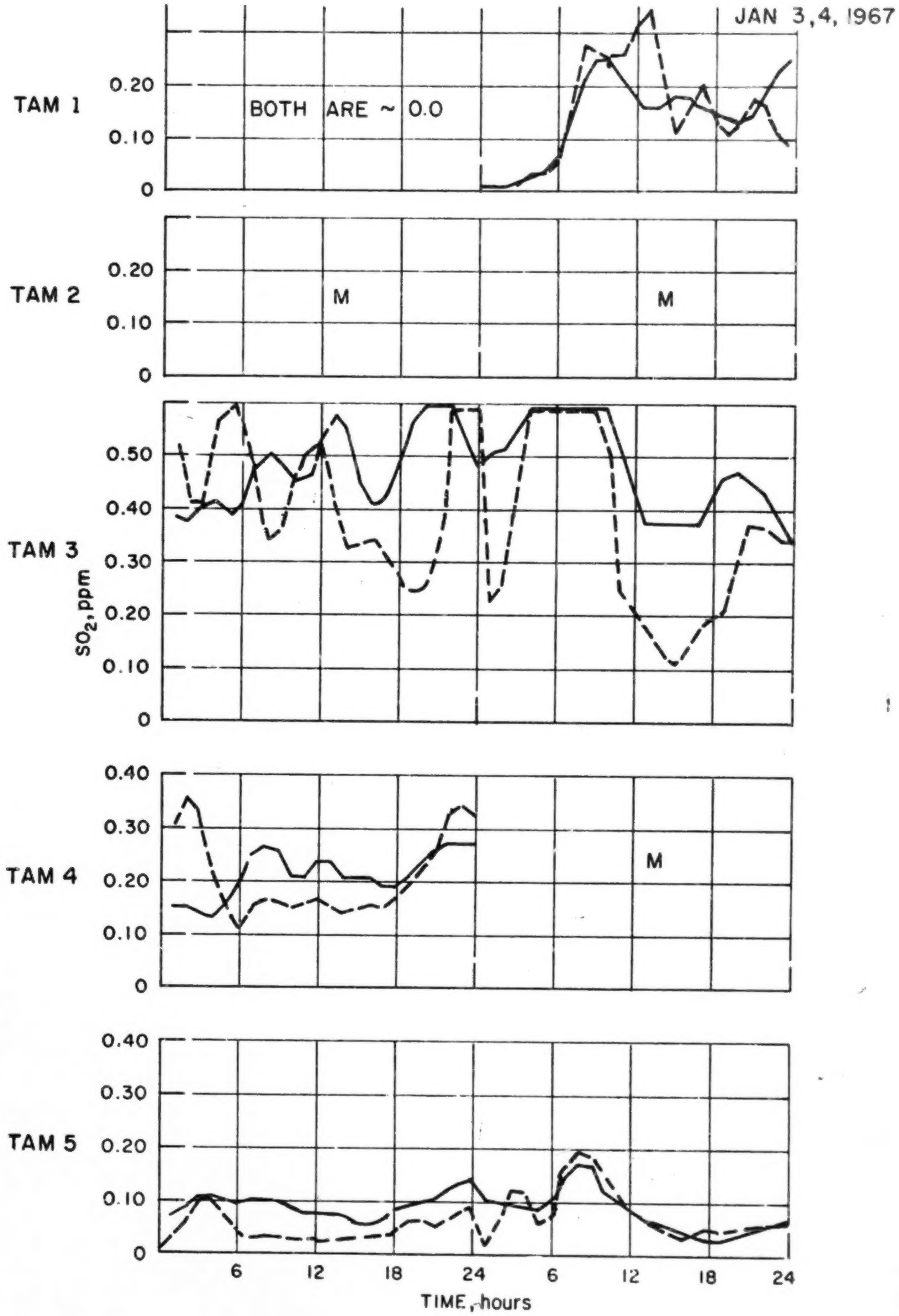

STAB
6
4
2
HLID, ft
2000
1000
0
TEMP, °F
40
20
0
WS, mph
20
10
0
WD, deg
360
180
0
1
12
24
12
24
12
24
12
24
'67 JAN:
29
30
31

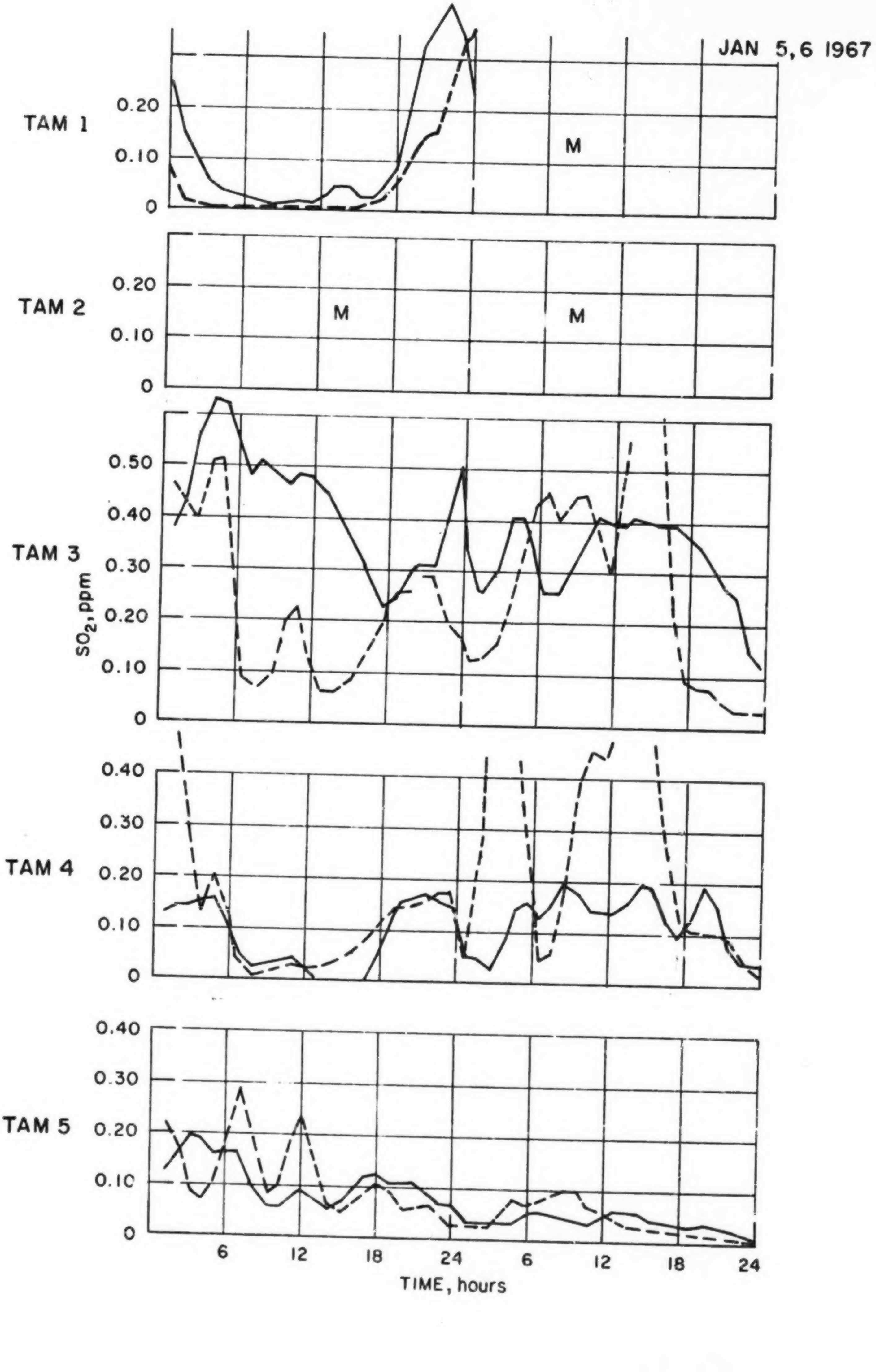
Fig. 6.3 Smoothed Hourly Values of SO_2 at TAM Stations 1-5. January 1967

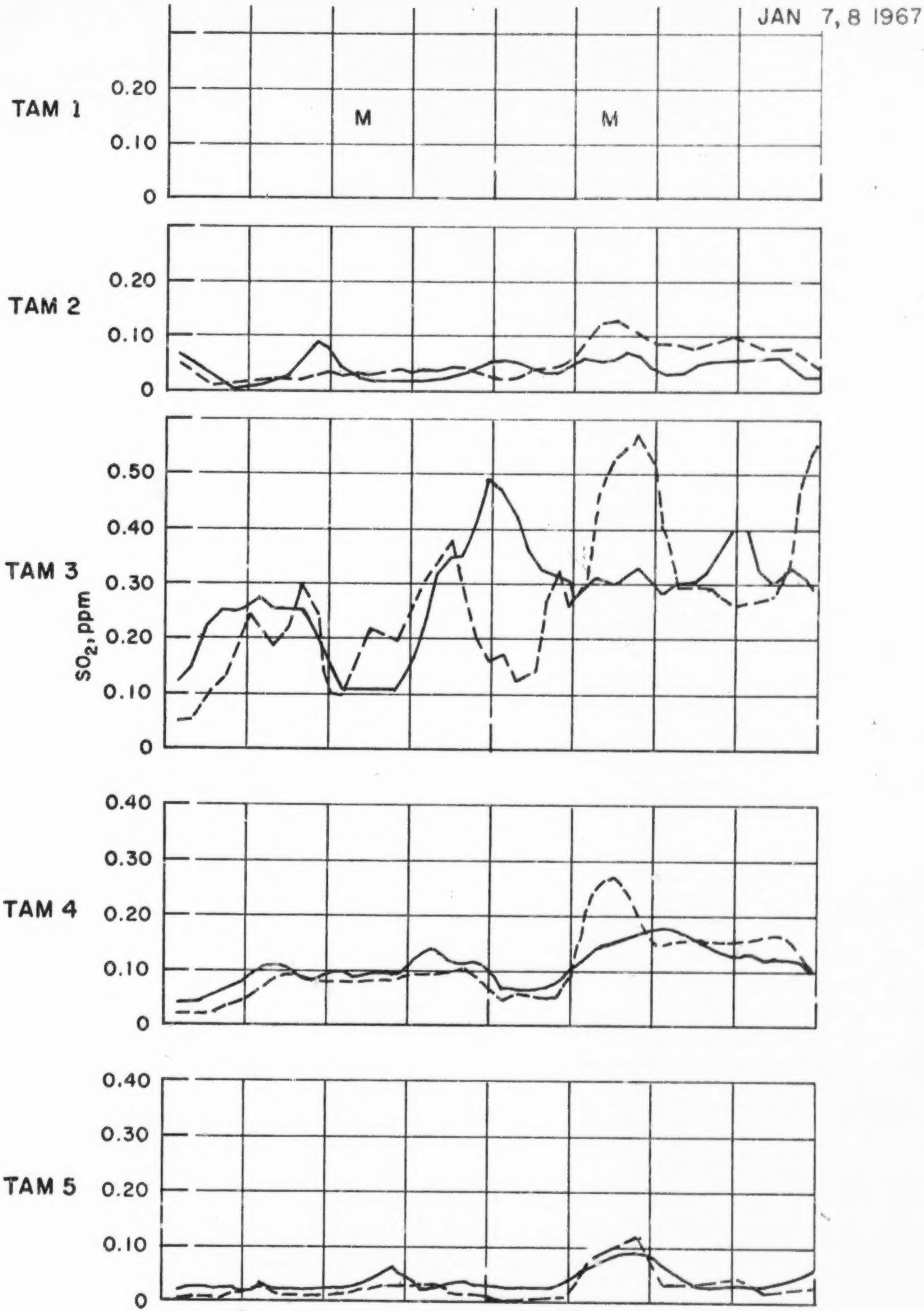
Observed ————————

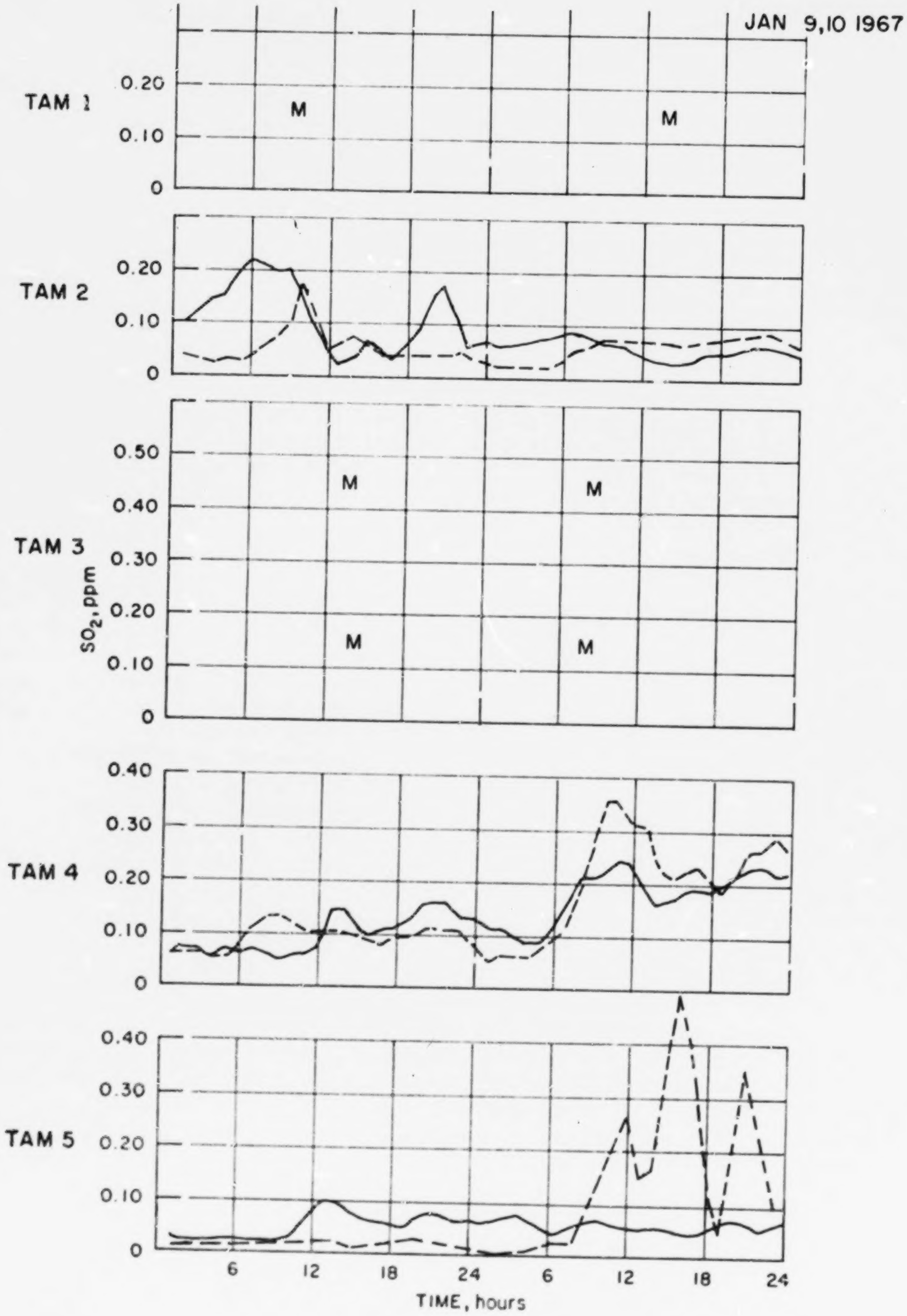
Estimated – – – – – –

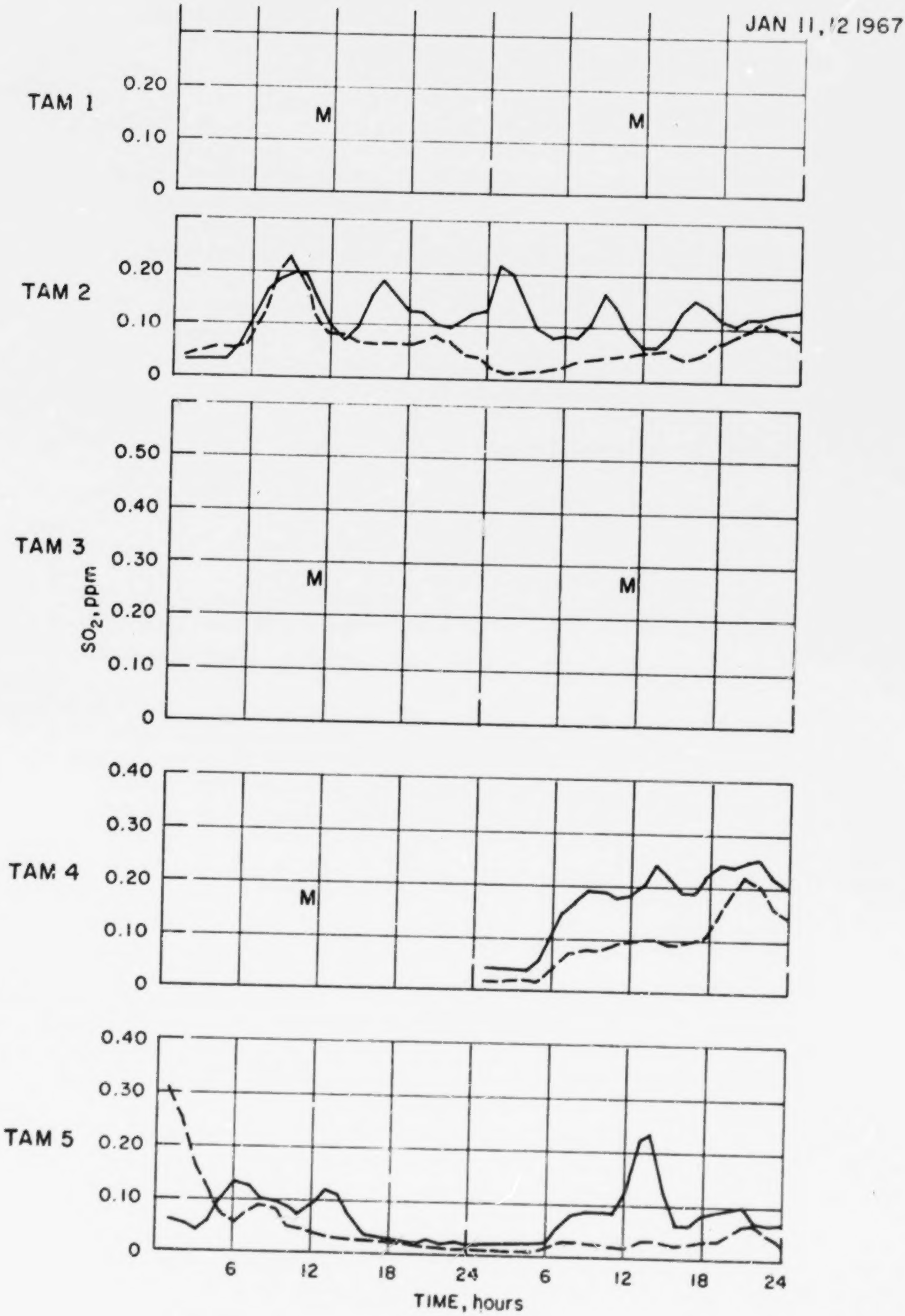

JAN 1,2 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
M
M
M
SO$_2$, ppm
0.50
0.40
0.30
0.20
0.10
0
6
12
18
24
6
12
18
24
TIME, hours

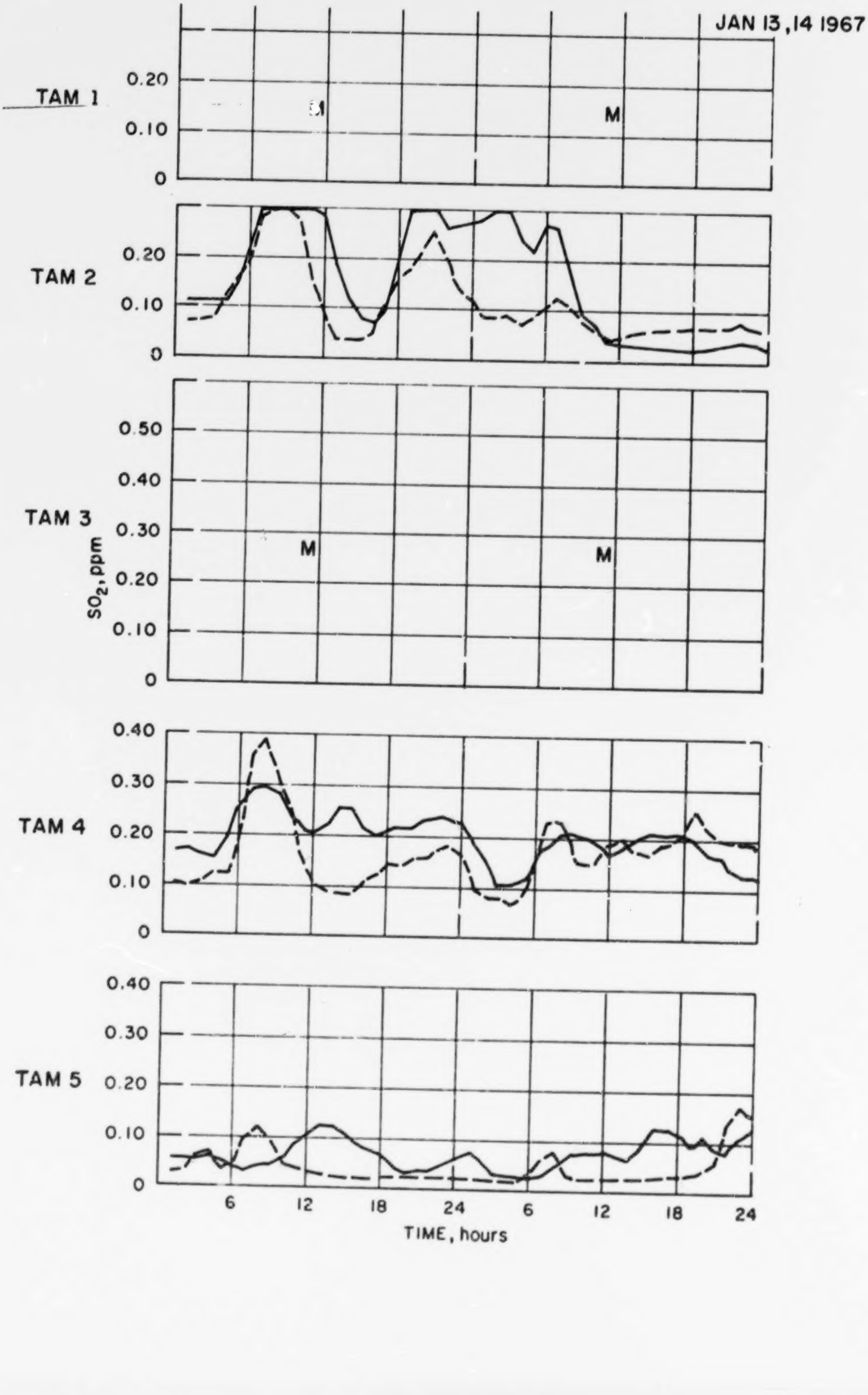

JAN 3,4, 1967
TAM 1
BOTH ARE ~ 0.0
TAM 2
M
M
TAM 3
TAM 4
M
TAM 5
SO$_2$, ppm
0
0.10
0.20
0.30
0.40
0.50
6
12
18
24
6
12
18
24
TIME, hours

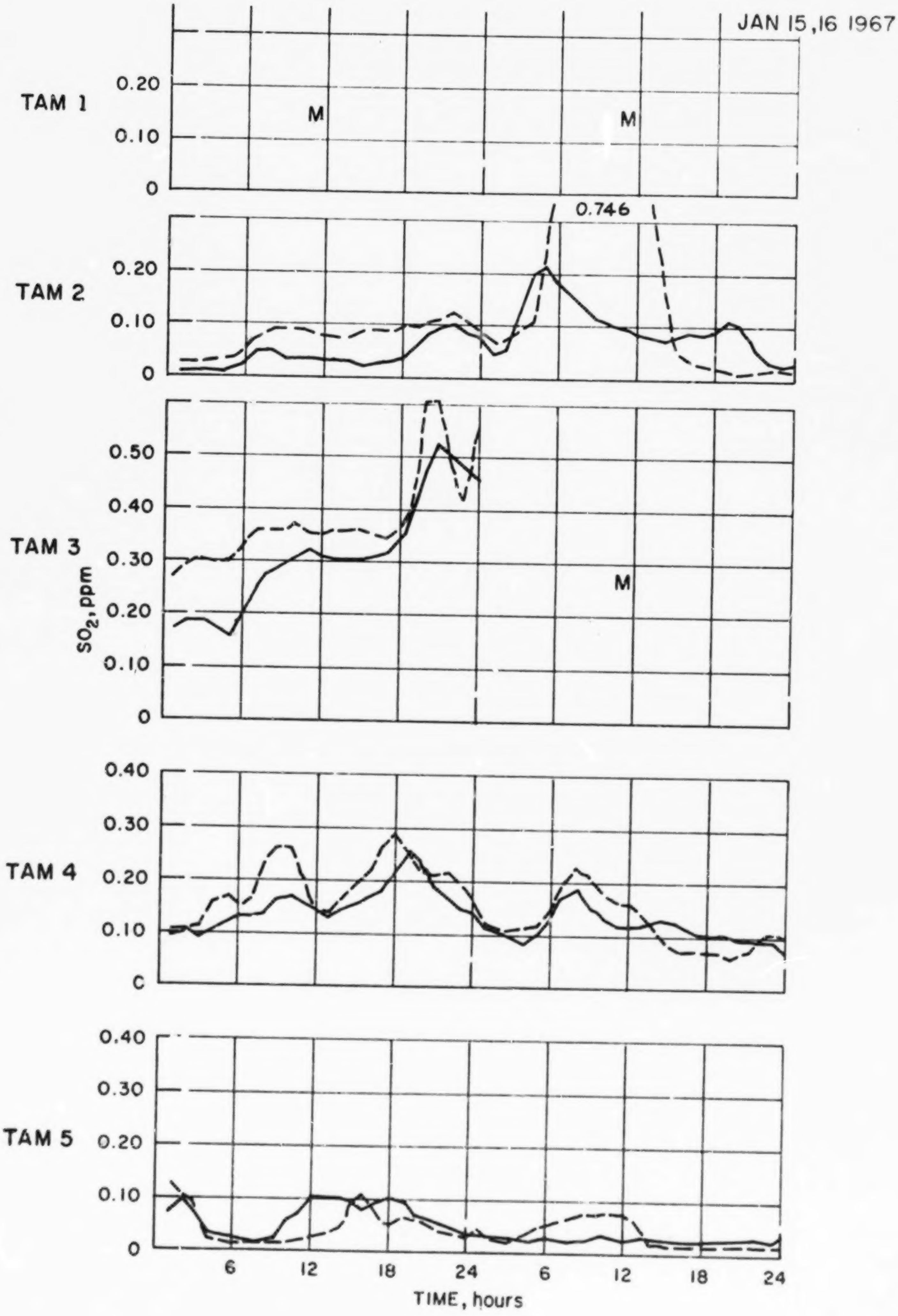

JAN 5,6 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
M
M
M
0.20
0.10
0
0.50
0.40
0.30
0.20
0.10
0.40
0.30
0.20
0.10
SO2, ppm
6
12
18
24
6
12
18
24
TIME, hours

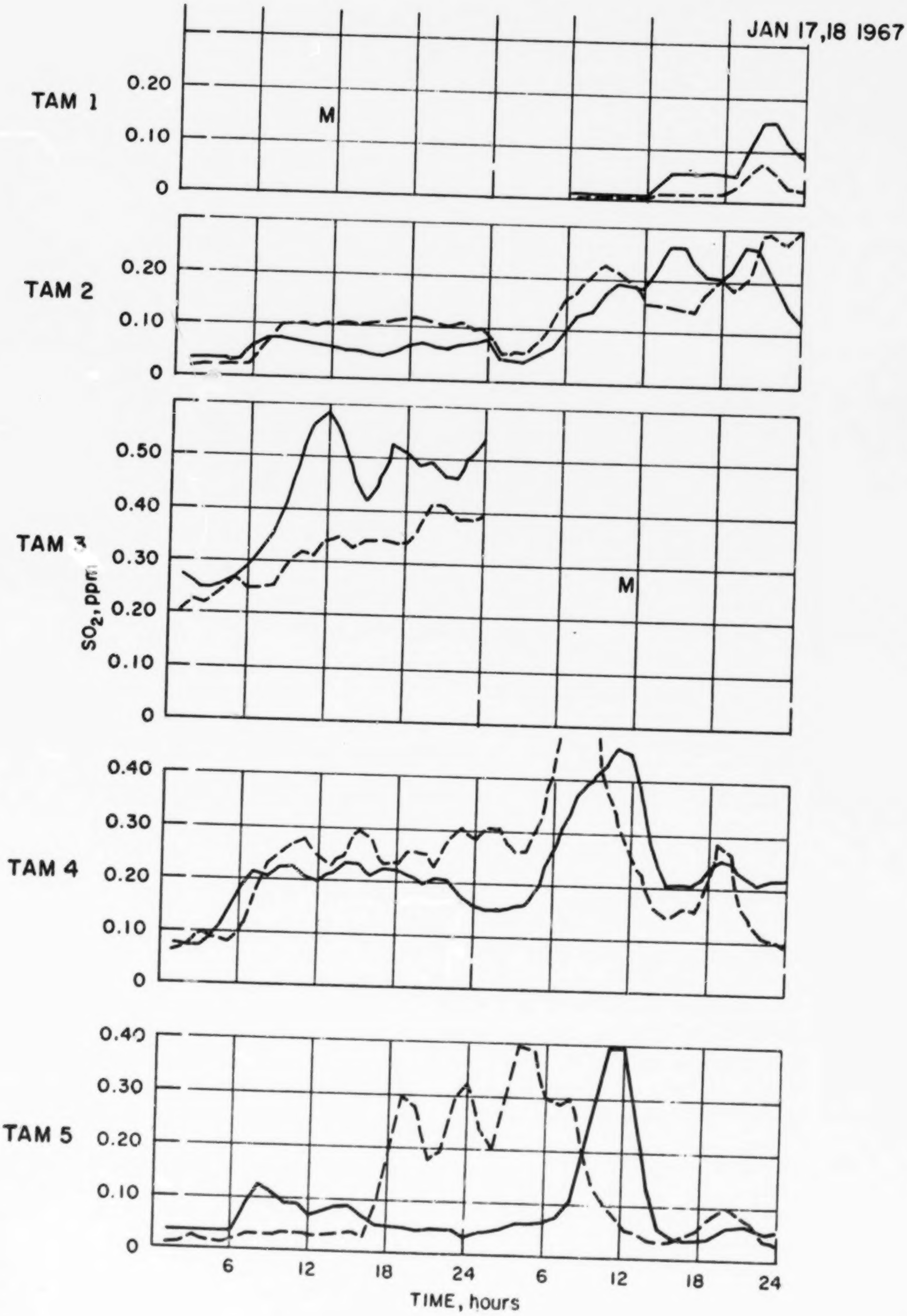

JAN 7, 8 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
M
M
SO$_2$, ppm
0
0.10
0.20
0.30
0.40
0.50
6
12
18
24
TIME, hours

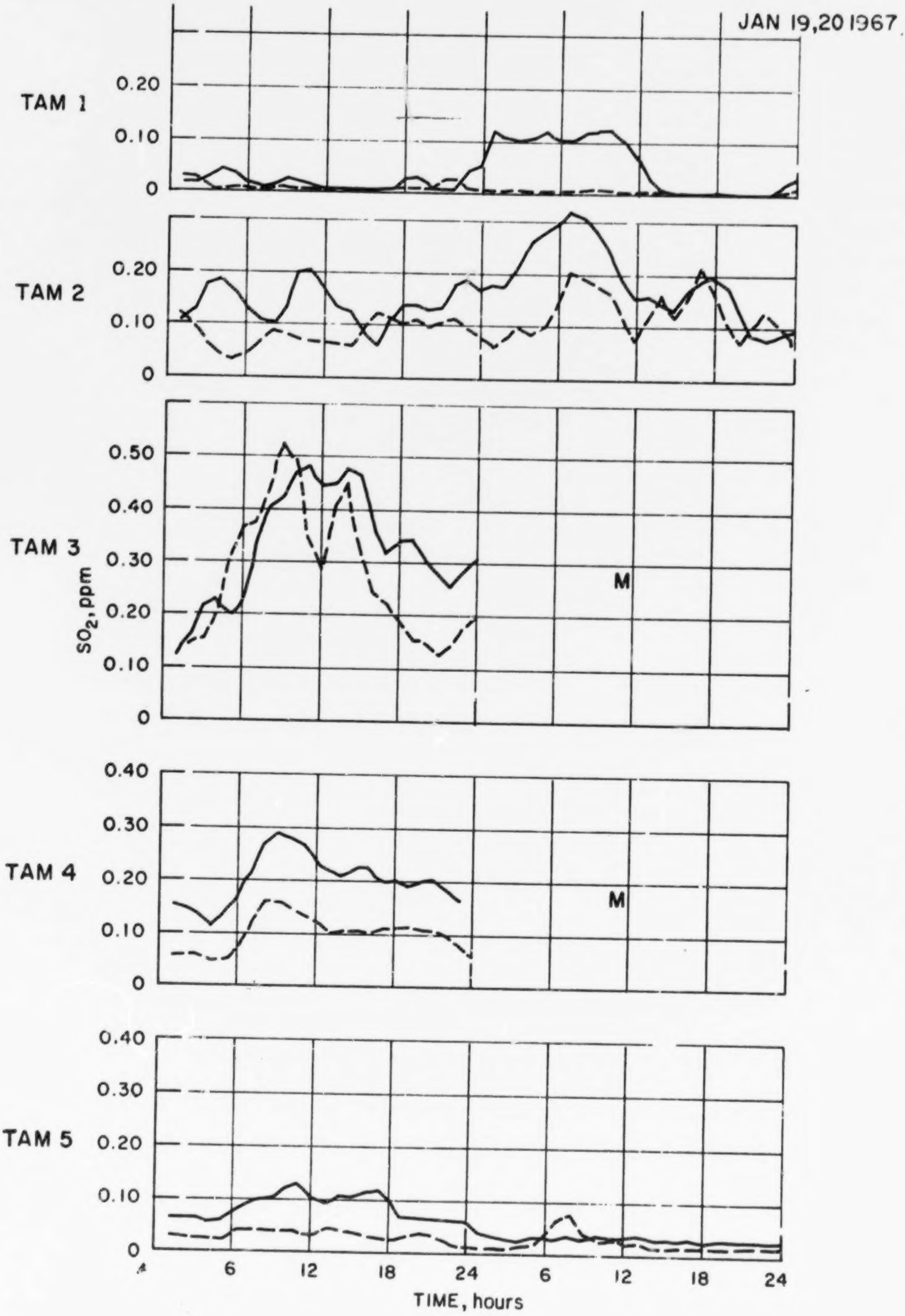

JAN 9,10 1967
TAM 1
0.20
0.10
0
M
M
TAM 2
0.20
0.10
0
TAM 3
SO_2, ppm
0.50
0.40
0.30
0.20
0.10
0
M
M
M
M
TAM 4
0.40
0.30
0.20
0.10
0
TAM 5
0.40
0.30
0.20
0.10
0
6
12
18
24
6
12
18
24
TIME, hours

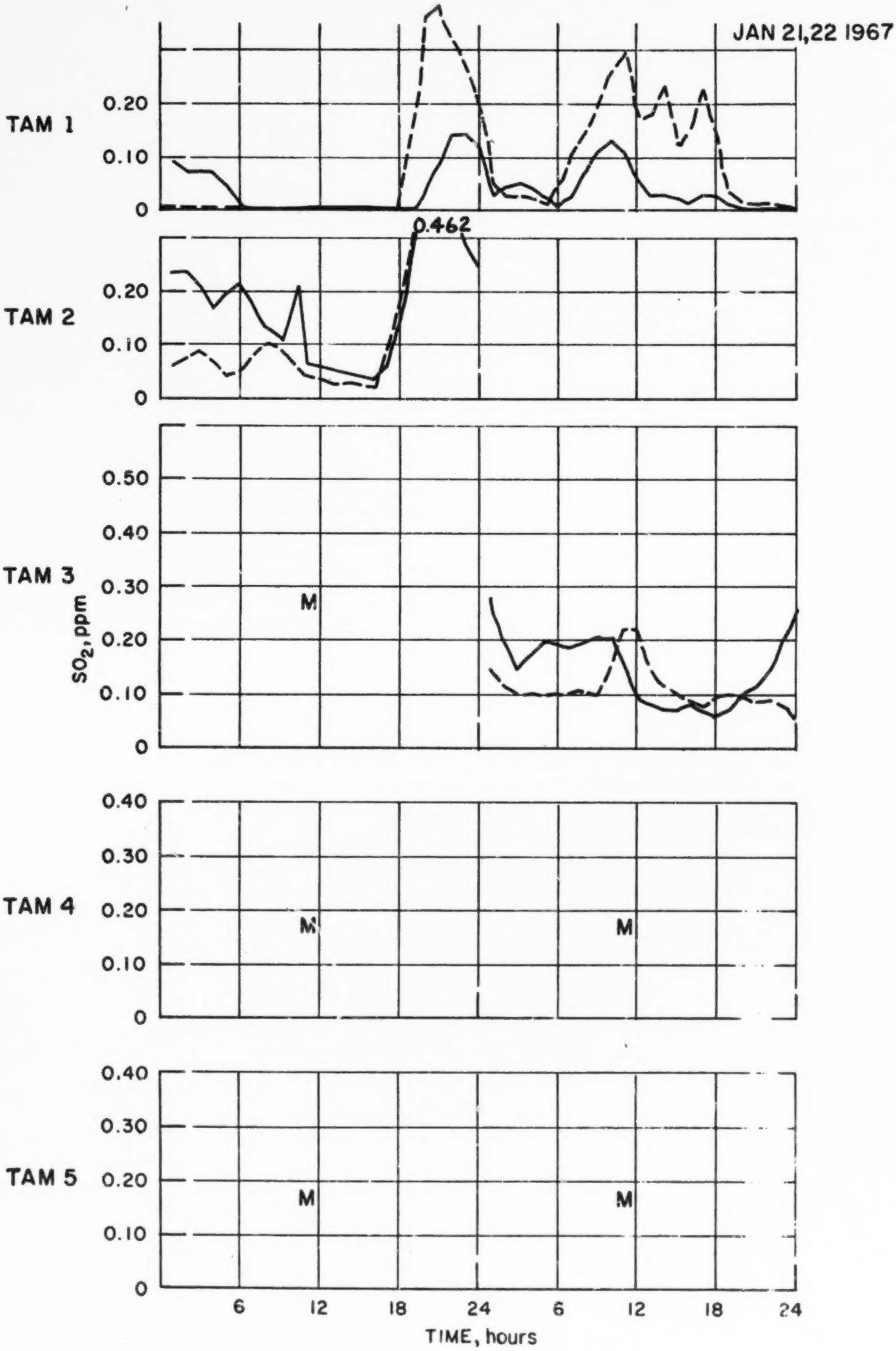

JAN 11, 12 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
M
SO$_2$, ppm
0
0.10
0.20
0.30
0.40
0.50
6
12
18
24
TIME, hours

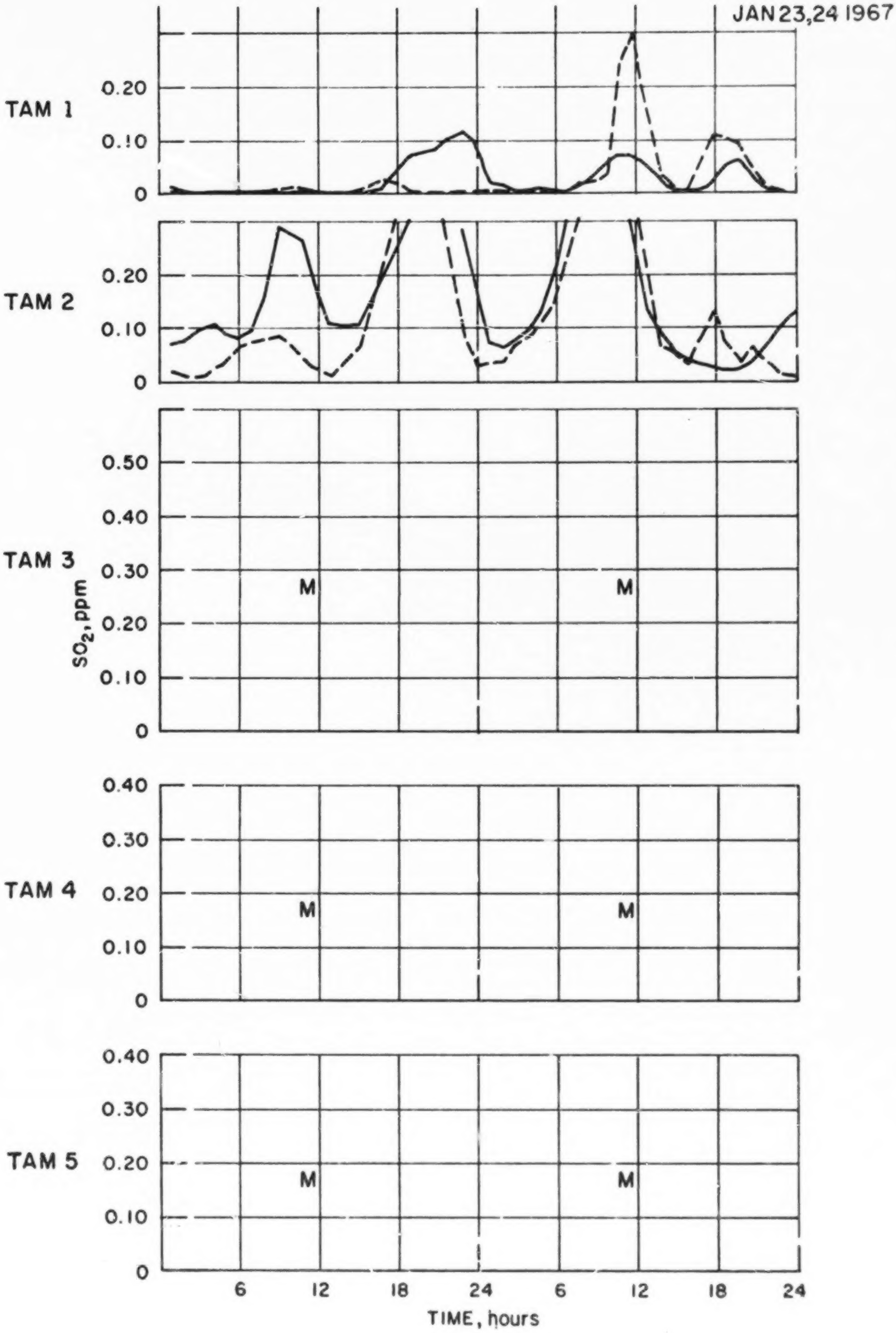

JAN 13,14 1967
TAM 1
0.20
0.10
0
M
M
TAM 2
0.20
0.10
0
TAM 3
0.50
0.40
0.30
0.20
0.10
0
SO_2, ppm
M
M
TAM 4
0.40
0.30
0.20
0.10
0
TAM 5
0.40
0.30
0.20
0.10
0
6
12
18
24
6
12
18
24
TIME, hours

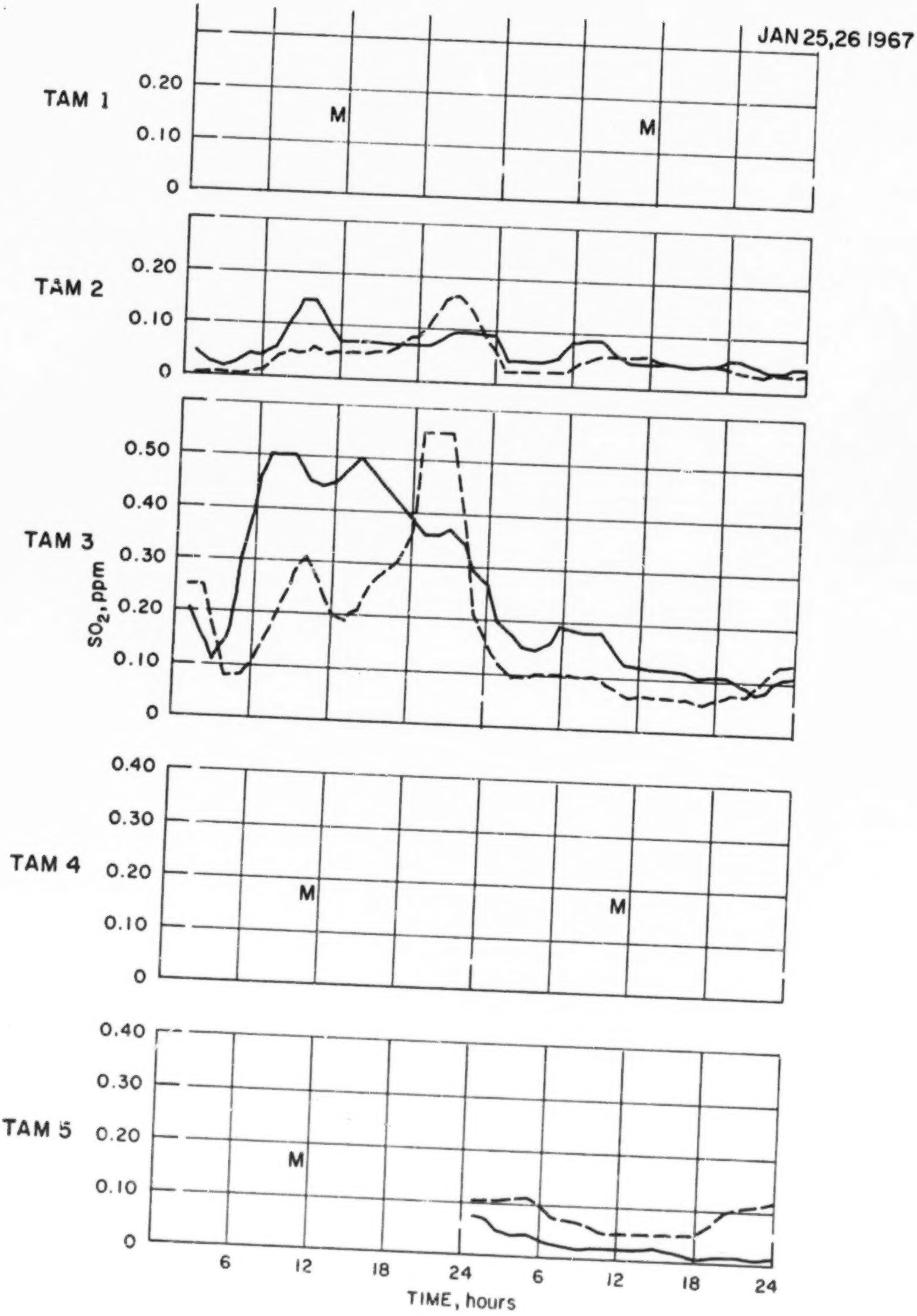

JAN 15,16 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
M
M
M
0.746
SO$_2$, ppm
0.50
0.40
0.30
0.20
0.10
0
6
12
18
24
TIME, hours

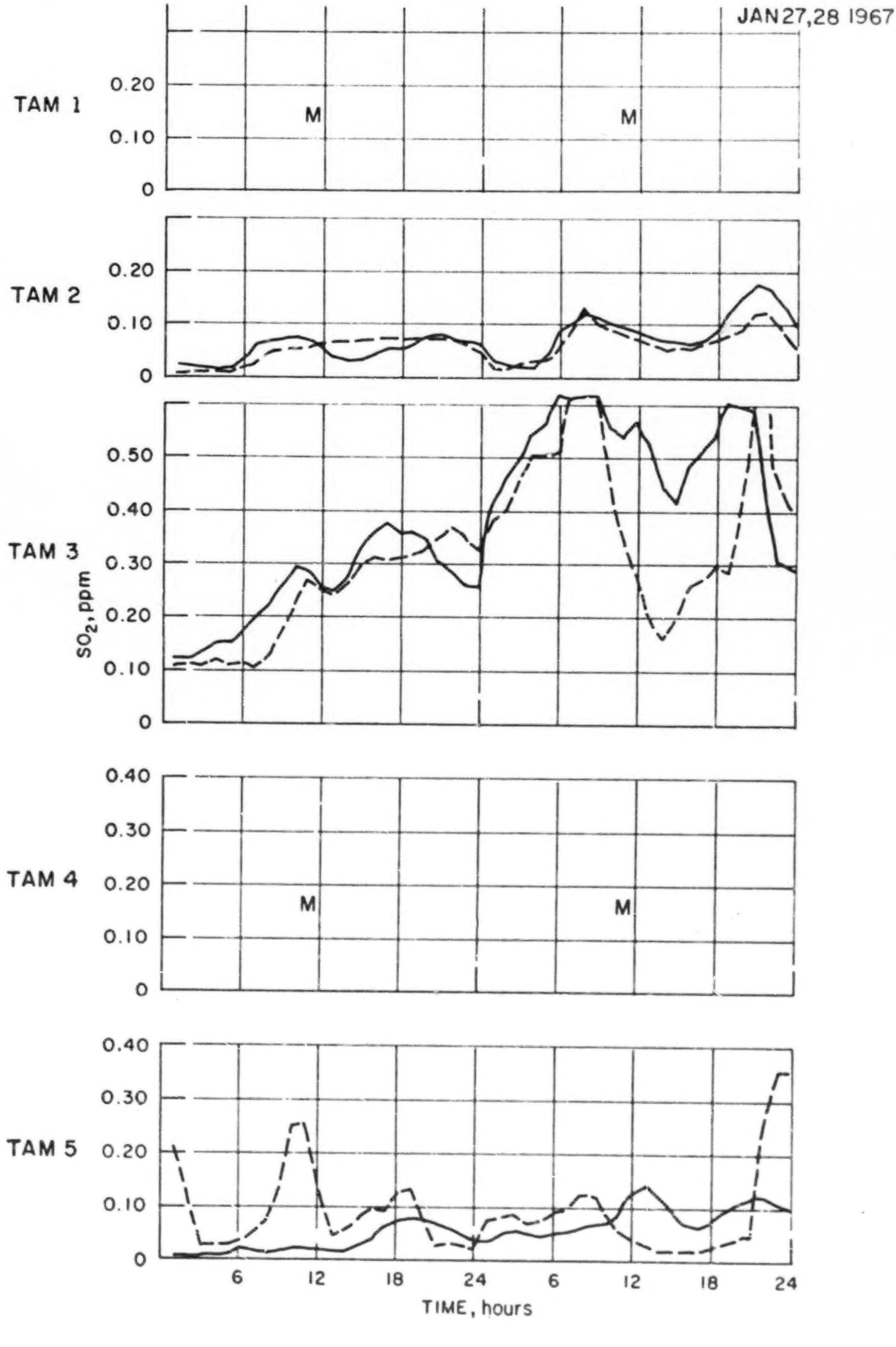

JAN 17,18 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
M
M
SO$_2$, ppm
0.20
0.10
0
0.50
0.40
0.30
0.20
0.10
0
0.40
0.30
0.20
0.10
0
6
12
18
24
6
12
18
24
TIME, hours

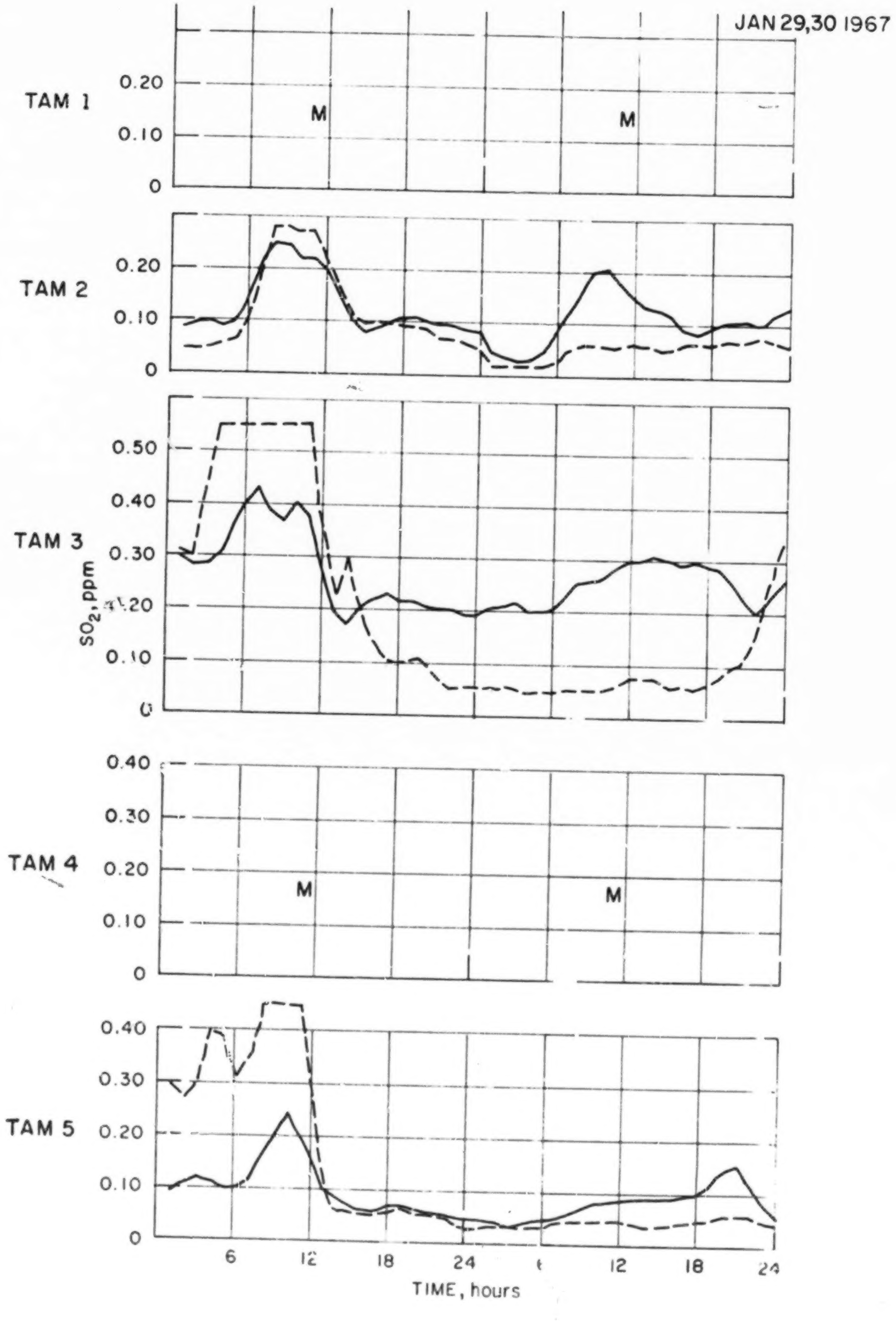

JAN 19,20 1967
TAM 1
0.20
0.10
0
TAM 2
0.20
0.10
0
TAM 3
0.50
0.40
0.30
0.20
0.10
0
M
TAM 4
0.40
0.30
0.20
0.10
0
M
TAM 5
0.40
0.30
0.20
0.10
0
SO_2, ppm
6
12
18
24
6
12
18
24
TIME, hours

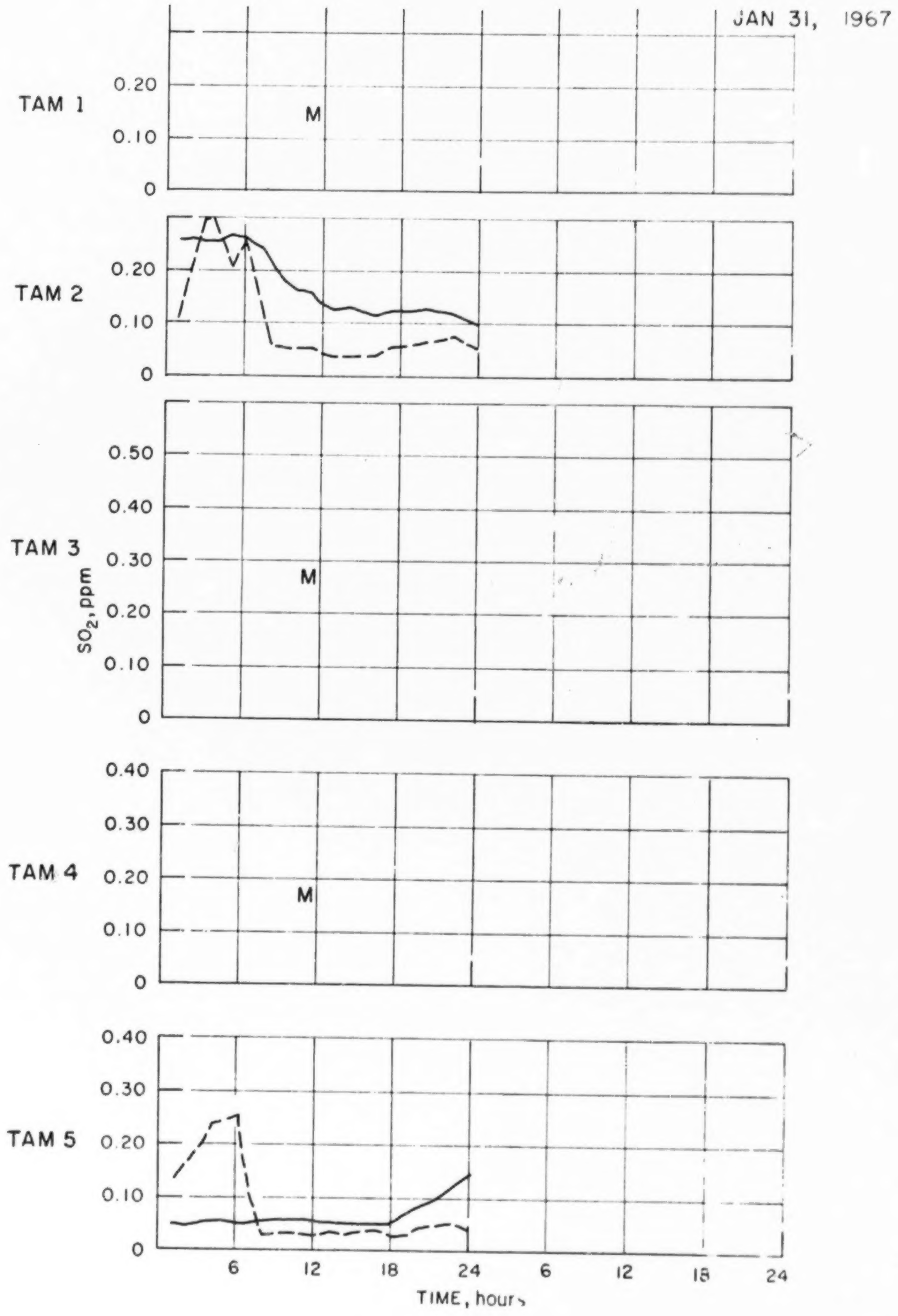

JAN 21,22 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
0.462
M
SO₂, ppm
0
0.10
0.20
0.30
0.40
0.50
6
12
18
24
TIME, hours


JAN 23,24 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
SO₂, ppm
0
0.10
0.20
0.30
0.40
0.50
M
M
6
12
18
24
TIME, hours


JAN 25,26 1967
TAM 1
0.20
0.10
0
M
M
TAM 2
0.20
0.10
0
TAM 3
0.50
0.40
0.30
0.20
0.10
0
SO$_2$, ppm
TAM 4
0.40
0.30
0.20
0.10
0
M
M
TAM 5
0.40
0.30
0.20
0.10
0
M
6
12
18
24
6
12
18
24
TIME, hours


JAN 27,28 1967
TAM 1
0.20
0.10
0
M
M
TAM 2
0.20
0.10
0
TAM 3
0.50
0.40
0.30
0.20
0.10
0
SO₂, ppm
TAM 4
0.40
0.30
0.20
0.10
0
M
M
TAM 5
0.40
0.30
0.20
0.10
0
6
12
18
24
6
12
18
24
TIME, hours


JAN 29,30 1967
TAM 1
TAM 2
TAM 3
TAM 4
TAM 5
M
M
M
M
0.20
0.10
0
0.50
0.40
0.30
SO$_2$, ppm
6
12
18
24
6
12
18
24
TIME, hours


JAN 31, 1967

TAM 1
0.20
0.10
0
M
TAM 2
0.20
0.10
0
TAM 3
0.50
0.40
0.30
0.20
0.10
0
SO_2, ppm
M
TAM 4
0.40
0.30
0.20
0.10
0
M
TAM 5
0.40
0.30
0.20
0.10
0
6
12
18
24
6
12
18
24
TIME, hours

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